University of Southampton

Faculty of Environmental and Life Sciences

School of Health Sciences

The Health of Movement

Recognising Movement Choices in Individuals for Long-Term Health

by

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Thesis for the degree of Doctor of Philosophy

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<u>Abstract</u>

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Changes in movement quality, specifically how people coordinate movement, have been identified in people with pain, history of pain and linked to risk of injury, changes in performance and quality of life. The health of movement is a balance between how an individual uses their body to engage with life and an ability to display choices in movement coordination strategies (MCS). The aim of this thesis is to explore the concept that assessing and retraining MCS improves the health of movement. Five core publications are included: two theoretical papers detailing the concept for assessing and retraining MCS; one reliability study establishing robustness of an assessment tool; a case report demonstrating validity and proof-of-concept of assessment and retaining of MCS; and a morphological study of the serratus anterior muscle illustrating knowledge of anatomical architecture can shape retraining strategies.

The commentary includes the following topics: i) theoretical concept for assessing and restoring the health of movement (Chapter 2); ii) aspects of anatomy and neurophysiological function to support methods of assessment and retraining (Chapter 3); iii) assessment of loss of movement choices (LMC) using cognitive movement control tests to inform retraining (Chapter 4); iv) cognitive movement retraining/movement coaching, a person-centred clinical reasoning framework to design individual tailored programmes to restore LMC (Chapter 5); v) General discussion - significance, implementation and impact, illustrated over 25 years (Chapter 6).

Results have demonstrated: i) good inter-rater and excellent intra-rater reliability for the assessment tool; ii) testing for LMC can inform retraining and cognitive movement retraining can change biomechanical and neurophysiological measures; and iii) novel findings of morphologically distinct subdivisions of serratus anterior.

This thesis recommends the assessment of MCS to guide retraining to improve the health of movement. Theoretical concepts presented and research conducted have provided evidence for proof-of-concept and validity and reliability of assessment procedures.

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Research Thesis: Declaration of Authorship

Sarah Louise Mottram

The Health of Movement

Recognising Movement Choices in Individuals for Long-Term Health

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:-
    - Dingenen, B., Blandford, L., Comerford, M., Staes, F. & Mottram, S. 2018. The assessment of movement health in clinical practice: A multidimensional perspective. Phys Ther Sport, 32, 282-292.
    - Mischiati, C. R., Comerford, M., Gosford, E., Swart, J., Ewings, S., Botha, N., Stokes, M. & Mottram, S. L. 2015. Intra and inter-rater reliability of screening for movement impairments: movement control tests from the foundation matrix. J Sports Sci Med, 14, 427-40.
    - Mottram, S. & Blandford, L. 2020. Assessment of movement coordination strategies to inform health of movement and guide retraining interventions. Musculoskelet Sci Pract, 45, 102100.
    - Mottram, S., Warner, M., Booysen, N., Bahain-Steenman, K. & Stokes, M. 2019. Retraining in a Female Elite Rower with Persistent Symptoms Post-Arthroscopy for

Femoroacetabular Impingement Syndrome: A Proof-of-Concept Case Report. J. Funct. Morphol. Kinesiol., 4.

- Webb, A. L., O'Sullivan, E., Stokes, M. & Mottram, S. 2018. A novel cadaveric study of the morphometry of the serratus anterior muscle: one part, two parts, three parts, four? Anat Sci Int, 93, 98-107.

Signature: Date: 20th March 2021

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I have worked with inspirational colleagues, from many different professions, who share my passion to champion movement as a key element to change quality of life. Thanks go to Mark Comerford with whom I have worked for the last 25 years. His belief in the fundamental concept of the systematic analysis of movement inspired the journey we have travelled together as we developed an education business, Comera Movement Science. Comera Movement Science, now part of Comera Group, champions education and technological innovations blending functional biomechanics and neuroscience research for the best current practice. Lincoln Blandford and the Comera Movement Science tutors have helped refine the evolution of movement assessment and retraining. I have collaborated with Suzanne Scott since early 2000 when she taught me the foundations of Pilates and the fundamentals of teaching movement. Since then, we have both explored movement in different environments and faced the challenges of high performance where movement faces the strength model. So many patients and clients have facilitated this journey too – thanks to you all.

A considerable amount of this thesis was written during the COVID-19 pandemic. I am grateful to Scilla Dyke who gave me unending support during this time and challenged me to reflect on my practice and movement coaching skills. James D'Silva whose Garuda method, encompassing intention, attention and enquiry, helped me to connect with mindful movement practice so relevant to the content within this thesis.

And of course, my family and friends who have supported my journey not only over the last year of writing this thesis, but also the 25 years of exploring the movement question.

Abbreviations

CMCT .... Cognitive Movement Control Tests

CNS .... Central Nervous System

FAIS...................................... Femoroacetabular Impingement Syndrome

FMS...................................... Functional Movement Screen

HLLMS.................................. Hip and Lower Limb Movement Screen

KT... Knowledge Transfer

LMC...................................... Loss of Movement Choices

MCS .... Movement Coordination Strategies

RCT .... Randomised Controlled Trial

SIS .... Subacromial Impingement Syndrome

TPM .... The Performance Matrix

WHO .... World Health Organisation

Chapter 1 Introduction, Movement for Health, Quality of Life and Aims of Thesis

1.1 Movement for health

The UK's Chief Medical Officers' physical activity guidelines offer a clear communication: 'If physical activity were a drug, we would refer to it as a miracle cure, due to the great many illnesses it can prevent and treat' (Department of Health and Social Care, 2019). Physical activity has a major impact on health, improves musculoskeletal conditions and mental health (Chekroud et al., 2018, Lee et al., 2012, Skou et al., 2018). Increasing and maintaining physical activity levels is crucial for health and the World Health Organisation's (WHO) global action plan aims to cut physical inactivity by 30% by 2030 (World Health Organisation, 2018). The COVID-19 pandemic has focused attention on health and physical activity, as those presenting with severe symptoms and those that have died from the disease, have a high prevalence of coexistent conditions including diabetes, cardiovascular disease and obesity (Apicella et al., 2020). The message is strong; we need more emphasis on enabling people to become active and remain active.

1.1.1 Movement quality

Physical activity is movement. McGonical neatly defines movement as 'using your body to engage with life' (Chatterjee, 2020, McGonigal, 2019). Changes in the way people move may influence their ability to be physically active, and use their body to engage with life, which ultimately influences their health.

Movement quality has been defined as the qualitative identification and rating of functional compensations, symmetries, impairments and/or efficiency of movement control in tasks, (e.g., walking and squatting) (Whittaker et al., 2017). Changes in movement quality, specifically how people coordinate movement, have been identified in people with pain, history of pain and fatigue (Worsley et al., 2013, Huygaerts et al., 2020, Luomajoki et al., 2008), and linked to risk of injury (Roussel et al., 2009b, Dingenen et al., 2015, Schuermans et al., 2017a, Rossi et al., 2020, Attwood et al., 2018). Motor coordination problems may affect psychosocial health and emotions (Li et al., 2019). With a clear goal of enabling people to become active and remain active, health, wellness and fitness professionals are recognising the importance of addressing movement quality (Roetert and Ortega, 2019, Blagrove et al., 2020). The focus of this thesis is on efficiency of movement control, in particular, **movement coordination strategies (MCS);** the clinically observable changes in the configuration of joints of the body (dynamic alignment) in individuals during the performance of a task.

1.1.2 Health promotion and the Health of Movement

Health promotion is the process of enabling people to increase control over factors that influence their health, and thereby improve their health (Tulchinsky and Varavikova, 2014). This thesis proposes that one factor influencing people's health is movement quality, and in particular, MCS. If we can empower people to influence their MCS to improve movement quality and subsequent health, this could be considered a worthwhile health promotion activity. Promotion of the health of movement is a focus of health policies and interventions (Roos et al., 2018).

1.1.3 Outlining the Health of Movement

The WHO's definition of health is complete physical, mental and social wellbeing, and not merely the absence of disease or infirmity (World Health Organisation, 2020a). This definition is limited by the dependence on a health professional identifying a disorder, which may or may not be problematical. A more inclusive definition is 'a state of balance, an equilibrium that an individual has established within themselves and between themselves and their social and physical environment' (Sartorius, 2006). This allows for a more social humanistic approach to health and acknowledges an individual's will and ability to act upon their feelings and desires to influence their health status (Gronblom Lundstrom et al., 2019).

Movement health may be informed by the ability of an individual to display choice in MCS (**Mottram and Blandford, 2020**), and is proposed to be a marker of the health of movement (**Dingenen et al., 2018**). The health of movement/movement health in this thesis is developed further and defined as a state, at any given time, which is a balance between how an individual uses their body to engage with life and an ability to display choices in MCS. This definition respects how an individual's movement is influenced by numerous constraints in the short-term, long-term and across the life-course (**Dingenen et al., 2018**) and their will and ability to act upon their feelings and desires. The connection between the terms and relationship to MCS is illustrated in **Figure 1.1**. Do we have to rethink the movement story and consider how the emergence, continuation and/or recurrence of pain and pathology is influenced by MCS, and equally important how this influences function and a person's potential to use their body to engage with life?

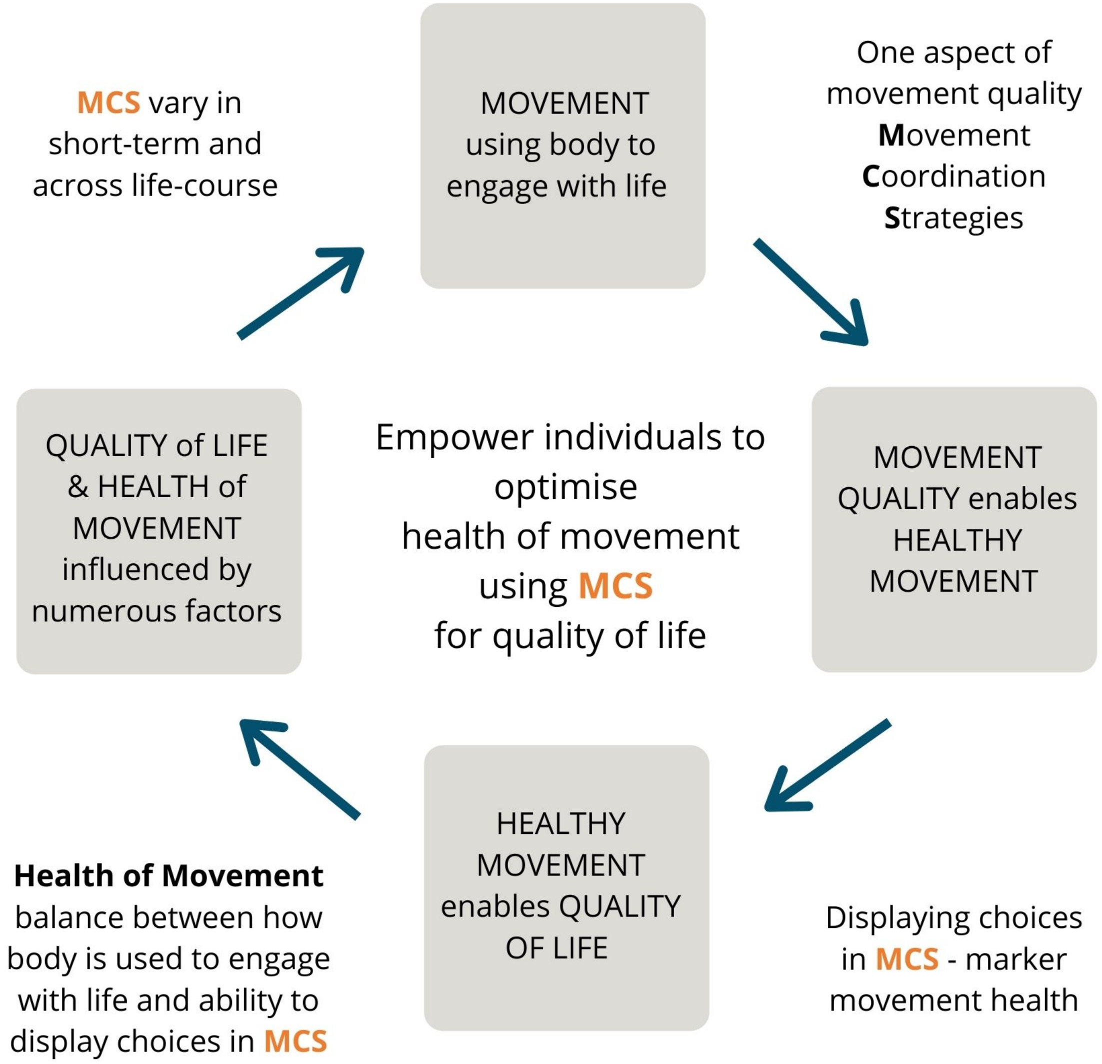

Figure 1.1 The health of movement

1.2 Proof-of-concept, theoretical frameworks and establishing robustness of assessment tools with five core publications

If MCS contribute to the status of the health of movement and influence quality of life, proof-of-concept needs to be established to guide definitive research, so practice can be informed. This commentary will discuss five original core publications, by the author including two theoretical papers developing concepts and a clinical reasoning framework (**Mottram and Blandford, 2020, Dingenen et al., 2018**); one reliability study to establish robustness of an assessment tool (**Mischiati et al., 2015**); one proof-of-concept case study including validity of concept **(Mottram et al., 2019**) and one original anatomical paper presenting the architectural morphometry of serratus anterior (**Webb et al., 2018a**). A summary sheet and copy of each publication are attached (page 95). Key elements are detailed in **Table 1-1 and highlighted in bold throughout the text**. Contributions, from the author of this thesis, to all publications are detailed in Appendix A.

Table 1-1 Key elements of five core publications included in this thesis

The five core publications are highlighted in bold throughout the text

Paper 1: Dingenen B, Blandford L, Comerford M, Staes F, **Mottram S. The assessment of movement health in clinical practice: A multidimensional perspective. (Dingenen et al., 2018)** ***(theoretical concepts)***

Historical models of movement assessment from **pathokinesiology** to **kinesiopathological** to new model of **movement health.** Presentation of rationale for the clinical assessment of **movement health** and key elements include:

1. A new model for assessing movement in clinical practice
2. 'The Movement Evaluation Model' focusing on emerging **movement coordination strategies (MCS)** from interaction of individual, task and environment constraints (**Figure 2.2**), with two assessment strategies:
    - **Evaluation of preferred movement patterns** (observing biomechanical patterns with kinematics)
    - Or **cognitive movement control evaluation** with **cognitive movement control tests** (**CMCTs;** testing for efficient movement control)
3. Clinical interpretation of findings from assessment of preferred movement patterns and cognitive movement control evaluation to inform retraining.

Paper 2: Mottram, S. and Blandford, L. **2020 Assessment of movement coordination strategies to inform health of movement and guide retraining interventions. (Mottram and Blandford, 2020)** ***(theoretical concepts)***

Rationale for clinical assessment of **MCS** and key elements include:

- Exploration of movement quality and movement as problem solving, i.e., individuals can vary movement solutions in response to a perpetual state of changing demands influenced by constraints

- Consideration of how wealth of degrees-of-freedom available in the movement system (i.e., motor abundance), adds variance (variability), gives the body ability to respond to unexpected perturbations with the changing environment (Latash, 2012) and provides potential for problem solving
- Discussion on how **altered MCS may illustrate** altered problem solving – may relate to specific constraints, as described in the dynamic systems model
- Presentation of the term **loss of movement choices (LMC)**
- Testing patterns of MCS with **cognitive movement control tests (CMCTS)**, to identify LMC, assessment procedure with examples
- **Restoring movement choices**
- Assessment and retraining of LMC within a clinical reasoning framework.

Paper 3: Mottram S, Warner M, Booysen N, Bahain-Steenman K, Stokes M. **Retraining in a female elite rower with persistent symptoms post-arthroscopy for femoroacetabular impingement syndrome: a proof-of-concept case report. (Mottram et al., 2019)** ***(proof-of-concept, validity of concept)***

This proof-of-concept case report supports hypothesis that testing MCS, with a battery of CMCTS, can inform a targeted **cognitive movement control retraining** strategy, and improve symptoms, activity limitations, participation/activity restrictions and quality of life, in an elite rower with persistent hip pain and femoroacetabular impingement syndrome (FAIS).

Rationale for exploring a movement-based approach in this rower was based on:

1. Biomechanical impairments are observed in people with FAIS (Diamond et al., 2018, King et al., 2018)
2. A relative dynamic anterior pelvic tilt results in an earlier occurrence of impingement in the arc of motion, whereas a relatively dynamic posterior pelvic tilt results in a later occurrence of impingement (Ross et al., 2014). Ten degrees of anterior pelvic tilt reduced the impingement-free range of motion arc of internal rotation by 5-9°. This is relevant to the provocative activity, hip flexion at catch phase in rowing
3. Control of lumbo-pelvic movements during hip flexion are important for rowing technique and performance
4. Previous physiotherapy had not included specific movement re-education.

The **targeted movement retraining programme**, linking results of assessment findings to individual targeted movement control retraining, changed biomechanical and neurophysiological measures, with less excursion of pelvic tilt and improved muscular control of the pelvis, in particular anterior tilt. These movement control issues were related to clinical presentation and requirements of the rowing stroke.

Paper 4: Webb A, O'Sullivan E, Stokes M, **Mottram S. A novel cadaveric study of the morphometry of the serratus anterior muscle: one part, two parts, three parts, four? (Webb et al., 2018a)** ***(anatomical architecture)***

Dissection study, presenting the **fascicular morphometry of serratus anterior**. The attachments sites were presented along with orientation and size of fascicles and physiological cross-sectional area. Three subdivision were described with a novel finding of two distinct fascicles attached to the superior and anterior aspects of rib 2. **Functional roles** were proposed for the different parts of **serratus anterior, in particular to controlling orientation of the scapula.**

Paper 5: Mischiati C, Comerford M, Gosford E, Swart J, Ewings S, Botha N, Stokes M, **Mottram S. Intra and inter-rater reliability of screening for movement impairments: movement control tests from The Foundation Matrix. (Mischiati et al., 2015)** ***(reliability of tests)***

This study established **acceptable** the **intra and inter-rater reliability**, of two experienced therapists' assessment of video recordings of **cognitive movement control tests,** from The Foundation Matrix. Twenty participants carried out nine tests and the therapists scored 39 questions. Accounting for right and left scores, where necessary, 75 criteria were evaluated for each participant. Real-time versus video recording was poor. Statistical limitations of Cohen Kappa's and intraclass correlation coefficient (ICC) were highlighted.

1.2.1 Twenty-five years of exploring the Health of Movement

Over the last 25 years, four key elements have led to the development of the concepts presented in this thesis (**Figure 1.2**).

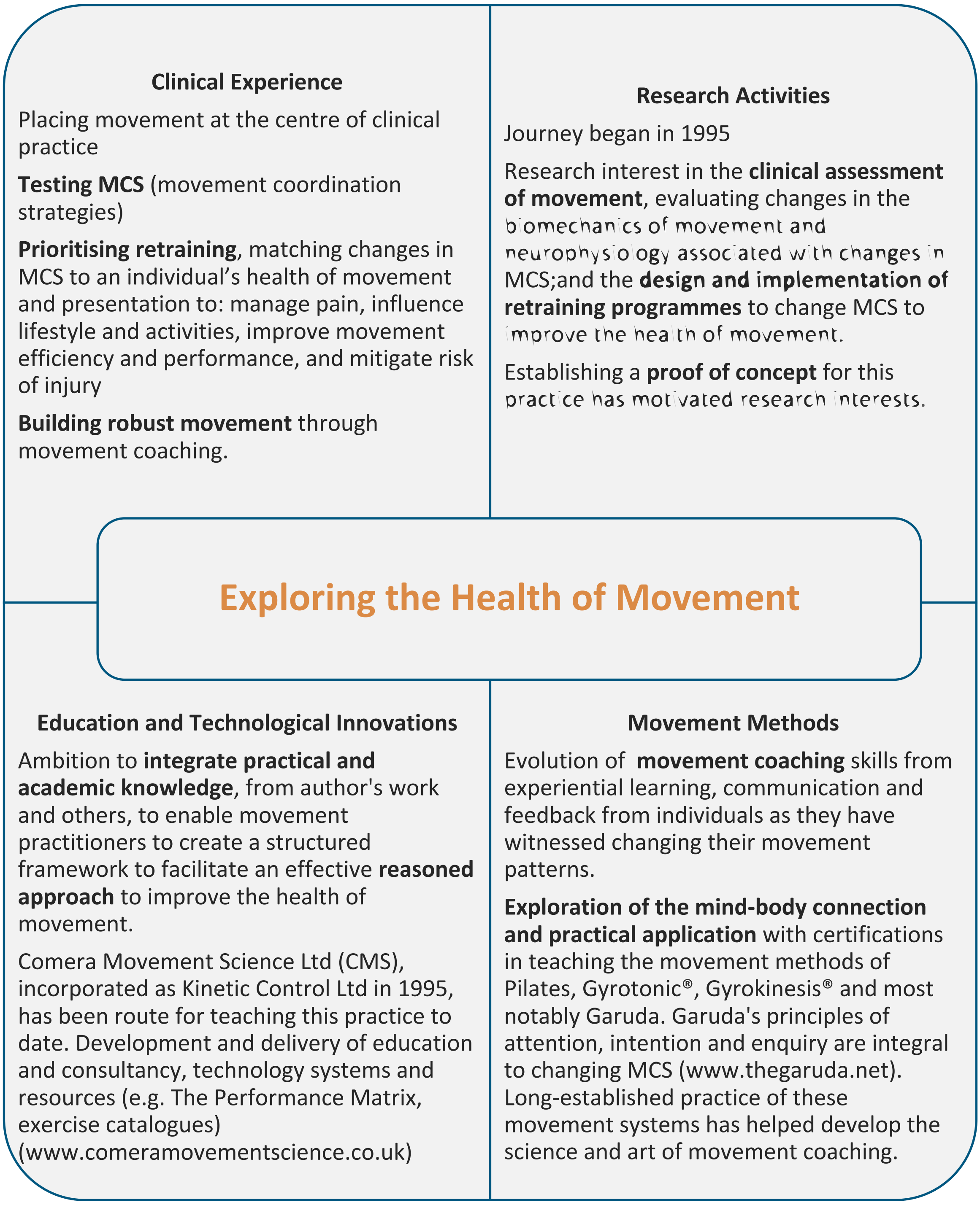

Figure 1.2 Four key elements, from the author's clinical-academic journey, contributing to the concepts presented in this thesis.

1.2.2 Published and related work in the commentary

Contributions by the author of this thesis to 30 peer reviewed publications, and one textbook, are detailed in Appendix A. Holding a post of Visiting Academic at the University of Southampton, UK since 2005, has led to seven collaborative publications with Maria Stokes, Professor of Musculoskeletal Rehabilitation, School of Health Sciences, University of Southampton and an opportunity to hold an Associate Membership at the Centre for Sport, Exercise and Osteoarthritis Research Versus Arthritis (comprising 6-universities, led by Queen's Medical Centre, Nottingham UK; Bath, Leeds, Loughborough, Oxford, Nottingham and Southampton). Further collaboration with researchers in Europe has included contributions to the clinical aspects of movement assessment and retraining in PhDs by Publication; Natalie Roussel, Universiteit Antwerpen, Belgium (Roussel et al., 2009b, Roussel et al., 2013, Roussel et al., 2009a); Filip Struyf, Vrije Universiteit, Belgium (Struyf et al., 2011a, Struyf et al., 2011c, Struyf et al., 2011b, Struyf et al., 2013, Struyf et al., 2014, Struyf et al., 2009); and Harpa Helgadottir, University of Iceland, Iceland (Helgadottir et al., 2010, Helgadottir et al., 2011).

1.3 Aims of thesis

This thesis explores the health of movement and how changes in the way people move, in particular MCS can influence how they use their body to engage with life.

The aim of this thesis is to present theoretical and research papers to support the concept that assessing and retraining MCS may improve the health of movement. This includes the presentation of theoretical concepts (**Mottram and Blandford, 2020, Dingenen et al., 2018**), research showing some proof-of-concept and the validity (**Mottram et al., 2019**) and reliability (**Mischiati et al., 2015**) of the assessment procedures and an anatomical study illustrating how understanding muscle morphology may direct training interventions (**Webb et al., 2018a**).

This commentary includes:

- The presentation of five core published papers **Table 1-1**
- Additional theoretical and researched-based publications to support the concept
- Reporting on how restoring MCS may influence pain, recurrent pain, pathology, lifestyle, activities, participation, movement efficiency, performance and mitigate risk of injury.

The specific aims are detailed in **Table 1-2**, which are addressed by the core papers in relation to specific chapters. Research includes studies on healthy people, people with pain, activity and participation limitations, youth to older people and people across the activity spectrum from less active to elite sports men and women.

The concept has been constantly evolving and refined through an iterative process, reflective practice and the advancing knowledge in the field. The commentary details the aims and nature of the research; the coherence between the published papers; how the material fits within the content of other work in the field and the nature and extent of the author's original contribution.

1.3.1 Structure of thesis

This thesis consists of seven chapters (**Figure 1.3**). The structure and content are outlined in **Table 1-2**.

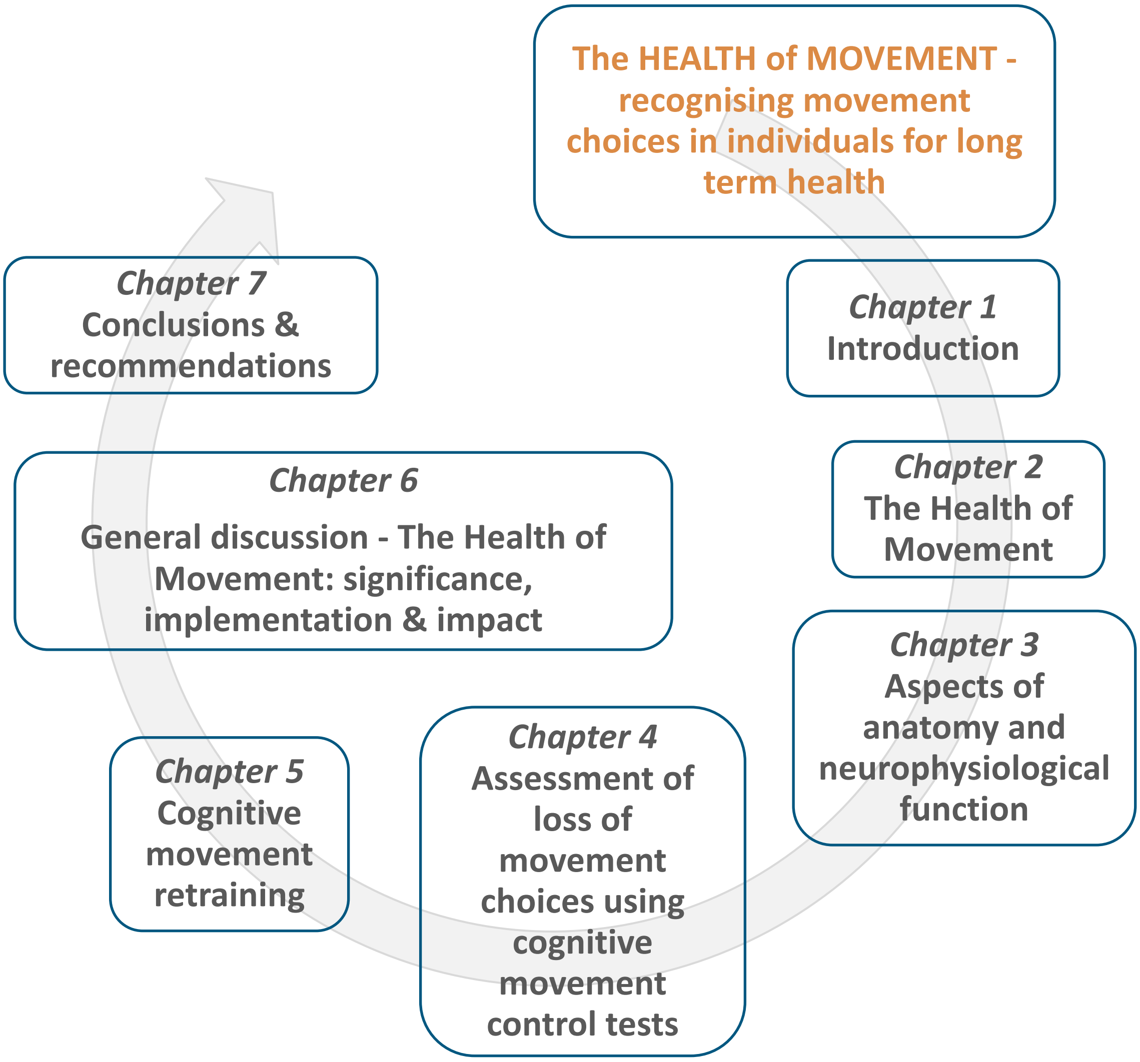

Figure 1.3 Illustration of the journey of the thesis across seven chapters

Table 1-2 Structure and content of thesis

Chapter 1: Introduction: The health of movement, movement quality, quality of life; aims of thesis
Exploring movement, health and **movement coordination strategies (MCS)**.
Chapter 2: The Health of Movement (**Dingenen et al., 2018, Mottram and Blandford, 2020**)
The concept for evaluating and restoring the health of movement, with theoretical publications. Aims to demonstrate: • MCS can be evaluated with **cognitive movement control tests (CMCTs)** • CMCTs can reveal inability to display choices in movement, termed **loss movement choices (LMC).**
Chapter 3: Aspects of anatomy and neurophysiological function (Webb et al., 2018a, Mottram et al., 2019)
Aims to illustrate how researched-based publications provide evidence to support the methods of assessment and retraining of MCS with: • An original anatomical article on serratus anterior morphometry, to inform movement retraining strategies • Proof-of-concept case study illustrating validity of assessment • Additional non-core papers.

Chapter 4: Assessment of loss of movement choices using cognitive movement control tests (Mischiati et al., 2015, Mottram and Blandford, 2020, Mottram et al., 2019)

The cornerstone of the concept, using cognitive movement control tests to reveal loss of movement choices to inform retraining.

Aims to demonstrate:

- Reliability of CMCTs
- Theoretical concepts and a clinical reasoning process
- Proof-of-concept case using CMCTs and use of The Foundation Matrix Movement Screen
- The clinical utility of CMCTs to identify LMC.

Chapter 5: Cognitive movement retraining (Mottram and Blandford, 2020, Mottram et al., 2019)

Personalised cognitive movement retraining plans directed by assessment of MCS.

Aims to demonstrate:

- Effect of movement control retraining with proof-of-concept case study
- A clinical reasoning framework directed by an individual's narrative, presentation and goals to change MCS to improve the health of movement.

Chapter 6: General Discussion - The Health of Movement: significance, implementation & impact

25 years of changing MCS and improving the health of movement.

Chapter 7: Conclusion and recommendations

Will you commit to the 'Health of Movement' movement?

Chapter 2 The Health of Movement

The relationship between the health of movement and movement coordination strategies (MCS) has been outlined in **Figure 1.1**. Changes in MCS have been identified in the presence of pain (Worsley et al., 2013, Botha et al., 2014, Luomajoki et al., 2008) and observed with altered kinematics (joint coordination) (Capobianco et al., 2018) and intermuscular coordination (muscle synergy coordination) (Claus et al., 2018) (**Figure 2.1**). This chapter sets out the concept for evaluating the health of movement, by evaluating intersegmental (joint) MCS. This thesis argues for the inclusion of assessing and retraining of MCS into current practice, to restore the health of movement for improved quality of life. Two of the core papers are discussed in this chapter to support this concept (**Mottram and Blandford, 2020, Dingenen et al., 2018**).

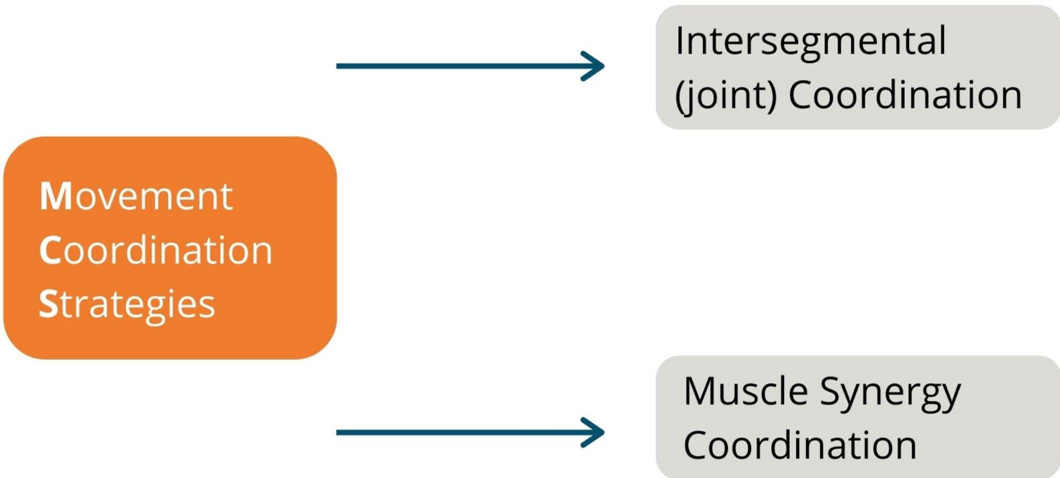

Figure 2.1 Movement coordination strategies: intersegmental (joint) and muscle synergy coordination

2.1 Movements patterns

2.1.1 The dynamic systems theory

The dynamic systems model proposes that an individual's movement patterns/outcomes emerge out of interaction of three domains, and their respective constraints (Holt et al., 2010, Newell, 1986). The domains are: i) the individual (e.g., co-morbidities, joint restrictions); ii) the task (e.g., walking); and iii) the environment (walking within confines of home or outdoors) and have been described previously (**Dingenen et al., 2018**).

In this thesis, movement evaluation focuses on the emerging MCS, at any given time, which is the result of the innumerable, and often latent contributing and interactive factors of the domains rather than on individual constraints (**Dingenen et al., 2018**) (**Figure 2.2**). There is support in rehabilitation environments for an optimal exercise-based protocol or modality, for a specific condition or constraint (Haroy et al., 2019, Malliaras et al., 2020, Kloskowska et al., 2016). However, there is growing support for the retraining of MCS for musculoskeletal conditions (Wilson et al., 2018, Worsley et al., 2013, **Mottram et al., 2019**). Rehabilitation protocols defined by a particular condition, constraint or pathology, may not address the complexity of individual presentations (Naunton et al., 2020).

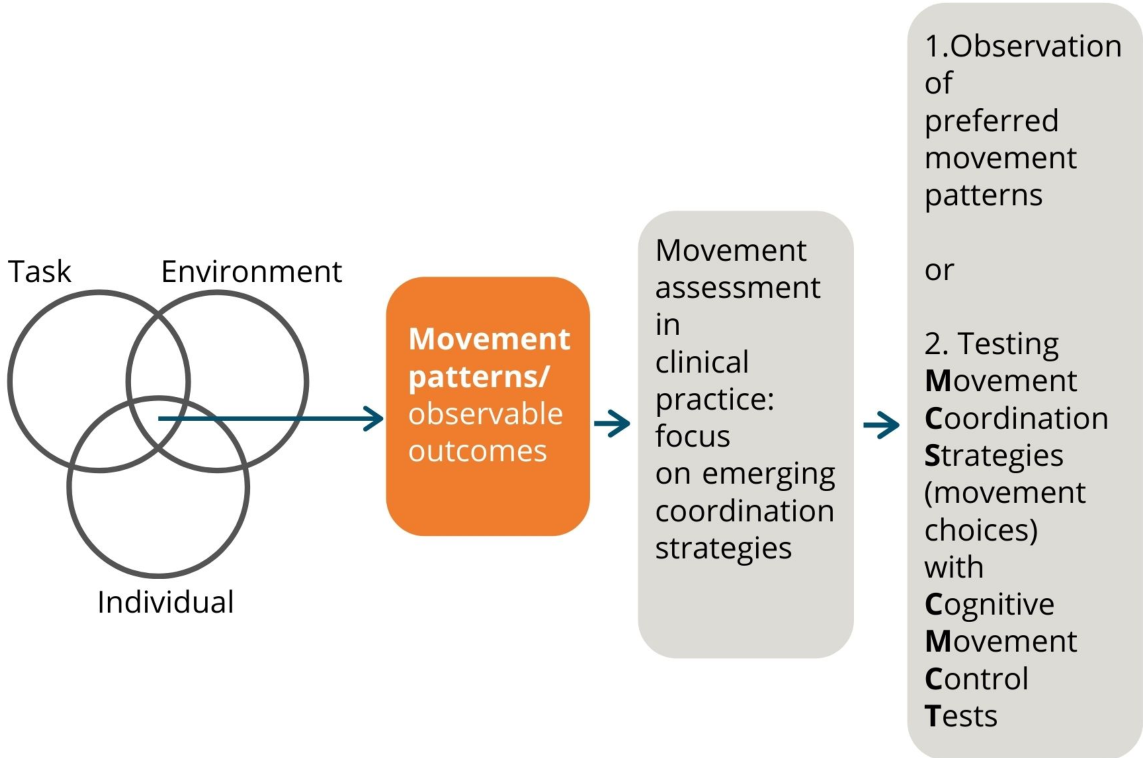

Figure 2.2 Movement is observed as the interaction of constraints of the individual, task and environment and assessed by evaluating movement coordination strategies (modified from Mottram and Blandford, 2020).

2.1.2 Evolving 'motor control'

Motor control is defined as an area of science exploring how the nervous system interacts with other body parts and the environment to produce purposeful, coordinated movements (Latash, 2012). Low argues motor control is 'a complex, broad and ambiguous concept within musculoskeletal physiotherapy' and raises the question 'when describing poor motor control, what does it mean and in what context?' (Low, 2018). The concept within this thesis proposes:

- 'Motor'/movement control is evaluated by assessment of MCS
- MCS are characterised by their attributes (i.e., coordination patterns)
- MCS are notated by describing their observable changes.

Evolution of the concepts are illustrated in Appendix B.

2.1.3 Are changes in movement coordination strategies part of the clinical picture?

The human movement system is designed to be able to reorganise MCS spontaneously in response to ever changing tasks and environmental constraints (Davids et al., 2003, Wikstrom et al., 2013). Alterations in MCS can be observed in the short-term (e.g., in the presence of pain) or the long-term, (e.g., years after anterior cruciate reconstruction) (Dingenen et al., 2018). Bittencourt advocates injury prediction should move from individual risk factor identification, to a complex model of risk pattern recognition (Bittencourt et al., 2016). Movement coordination strategies may emerge as being an important determinant in the patterns of interactions and the emerging injury risk. Neuromuscular training programmes, which include training elements to change dynamic alignment, coordination and motor skills, have been shown to improve movement quality (Kiesel et al., 2011), performance (Pasanen et al., 2009) and prevent injuries (Pasanen et al., 2008, Caldemeyer et al., 2020). Alterations in MCS have been noted in different cohorts (Worsley et al., 2013, Roussel et al., 2009b, Botha et al., 2014) including in individuals without pain (Warner et al., 2015, Hamill et al., 2012).

The assessment and restoration of MCS is considered for:

- Management of people in pain, recurrence of pain and with pathology
- Individuals seeking to change their lifestyle and increase participation in activities
- Improving performance, movement efficiency
- Mitigating risk of injury.

2.2 Assessment of movement coordination strategies

One of the core papers included in this thesis is a masterclass (**Dingenen et al., 2018**) presenting two approaches to evaluating MCS:

- Observation of preferred movement patterns
- Testing for patterns of MCS (choice in movement) (**Figure 2.2**).

Evaluation of preferred movement patterns are observed during a task (e.g., sit to stand), performed without any prior instruction on movement quality and can be considered biomechanically more or less advantageous for the person, at a particular point in time (**Dingenen et al., 2018**). However, evaluation of preferred movement patterns does not explore the ability of a person to cognitively influence MCS (choice). A second core paper details the concept of questioning the ability of an individual to alter MCS and is discussed throughout thesis **(Mottram and Blandford, 2020)**.

2.2.1 Variability in movement

Each individual moves differently; variability in movement is normal and is becoming increasingly recognised as an important marker of the health of movement (Hamill et al., 2012, Kiely, 2017). Variability of a movement outcome has been described as: i) the consistency in what is achieved (e.g., stride length in running), and ii) as coordination variability, the range of coordinative strategies exhibited whilst performing the movement outcome (Preatoni et al., 2013). Both of these types of variability can be high or low and Dingenen proposed a 'window' of variability in which healthy people function (**Dingenen et al., 2018**). Clinical groups (e.g., people with pain or altered proprioception) are observed to demonstrate both reduced and increased variability of movement (Madeleine et al., 2008, Baida et al., 2018, Nordin and Dufek, 2019). Reduced coordination variability has been associated with overuse injuries (Hamill et al., 2012). Movement coordination strategies vary within individuals, between trials of a task, and between individuals performing the same task (Needham et al., 2015, Hamill et al., 2012). This makes assessment challenging and highlights the need for finding clinic-ready solutions for assessing MCS, to identify reduced coordination variability to direct retraining and measure outcomes.

2.2.2 Clinical assessment of movement coordination strategies by testing choice in movement

The theoretical concept paper (**Mottram and Blandford, 2020**) presents how movement health is described by the ability to demonstrate access to motor abundance. The principle of motor abundance suggests the central nervous system has the ability to facilitate families of solutions (coordinated movements) equally able to solve a task, that are not the same over repeated trials (Latash, 2012). This abundance allows for adaptation across a variety of environmental conditions and helps the body deal with unexpected perturbations.

Testing choice in movement, by asking a person to move in a predetermined way, using **cognitive movement control tests (CMCTs)** is proposed to question the ability to access motor abundance and specific MCS; in contrast, observing preferred movement patterns relies on an individual selecting their own pattern (**Dingenen et al., 2018, Mottram and Blandford, 2020).**

Coordination variability is reported in the literature using kinematic measures (Desai and Gruber, 2020, Davis et al., 2019, Weir et al., 2019). A clinical assessment framework, not requiring technology, and the rationale for using CMCTs to question movement variability is described in one core paper (**Mottram and Blandford, 2020**). Cognitive movement control tests evaluate an individual's ability to cognitively coordinate movement at a specific joint or region (site) in a particular plane of movement (direction), under low and high threshold (Mottram and Blandford, 2020, Mottram and Comerford, 2008). An inability to access motor abundance and display choices in MCS, are defined as **loss of movement choices (LMC)**; notated by site, direction and threshold® (Mottram and Blandford, 2020, Mottram and Comerford, 2008) (**Figure 2.3**).

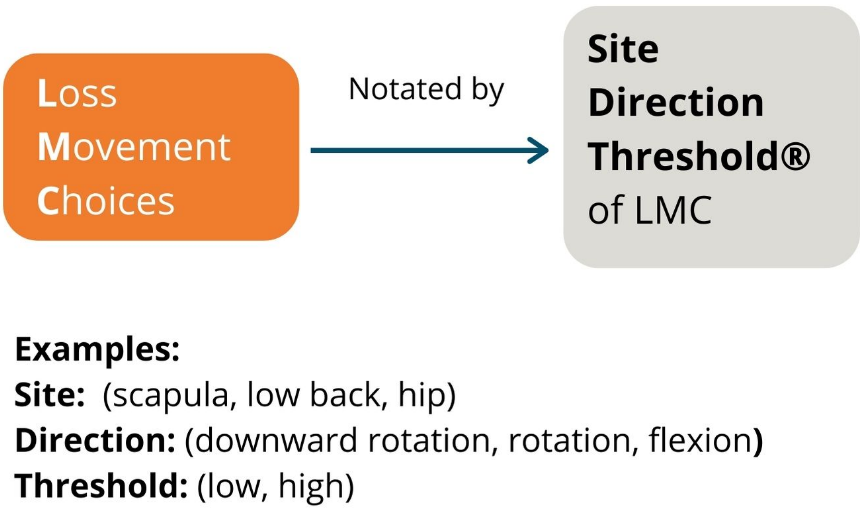

Figure 2.3 Loss of Movement Choices notated by Site, Direction and Threshold®

This thesis presents support for re-establishing motor abundance, lost movement choices and improving the health of movement by restoring MCS (**Figure 2.4**). Restoring loss of movement choices to optimise the health of movement is illustrated in (**Figure 2.5**) and discussed in Chapters 3 -5.

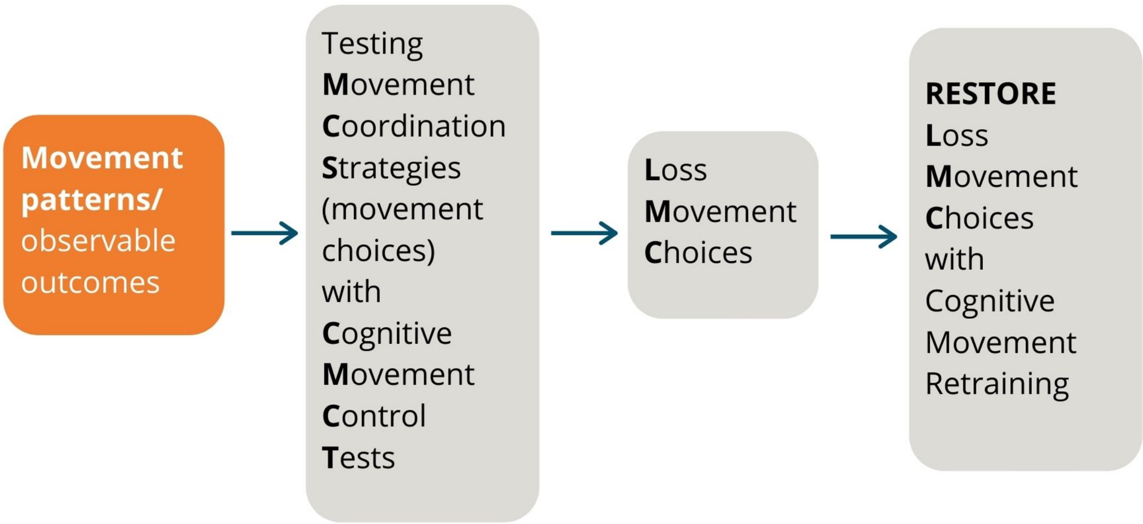

Figure 2.4 Testing for and restoring movement coordination strategies

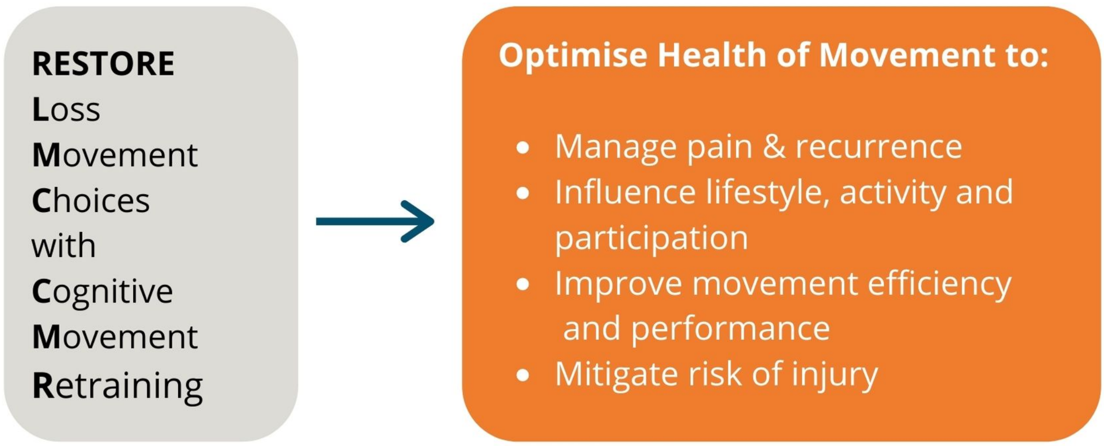

Figure 2.5 Restoring loss of movement choices to optimise the health of movement

2.3 Summary Chapter 2

Two core papers have been presented in this chapter (**Dingenen et al., 2018, Mottram and Blandford, 2020**). The theoretical concept for evaluating and restoring the health of movement have been outlined:

- Movement coordination strategies can be evaluated with CMCTs (see Chapter 4)
- CMCTs can reveal an inability to display choices in movement, termed loss of movement choices (LMC)
- LMC can be restored by cognitive movement retraining (see Chapter 5) **Figure 2.4**.

The next chapter explores aspects of anatomical and neurophysiological function to support the methods of assessment and retraining of MCS.

Chapter 3 Aspects of Anatomy and Neurophysiological Function

This chapter explores aspects of anatomical and neurophysiological function to strengthen the scientific basis underpinning measures of function and impairment. Two of the core papers are discussed; an original anatomical article of serratus anterior morphometry (**Webb et al., 2018a**), and a proof-of-concept case study illustrating the assessment of movement with movement analysis and electromyography technology (**Mottram et al., 2019**). Further relevant publications, by the author of this thesis, supporting kinematic and neurophysiological changes in different cohorts are presented.

3.1 Exploring the morphometry of Serratus Anterior

3.1.1 Background and scapular orientation

Serratus anterior is a key focus of training both in the rehabilitation and sports setting (Pieters et al., 2020, Cools et al., 2020). Serratus anterior is considered to be an important muscle in maintaining and controlling orientation of the scapula (**Webb et al., 2018a**). The background to the development of the serratus anterior morphometry paper is outlined in Appendix C. This includes the concept of controlling the orientation of the scapula in rehabilitation.

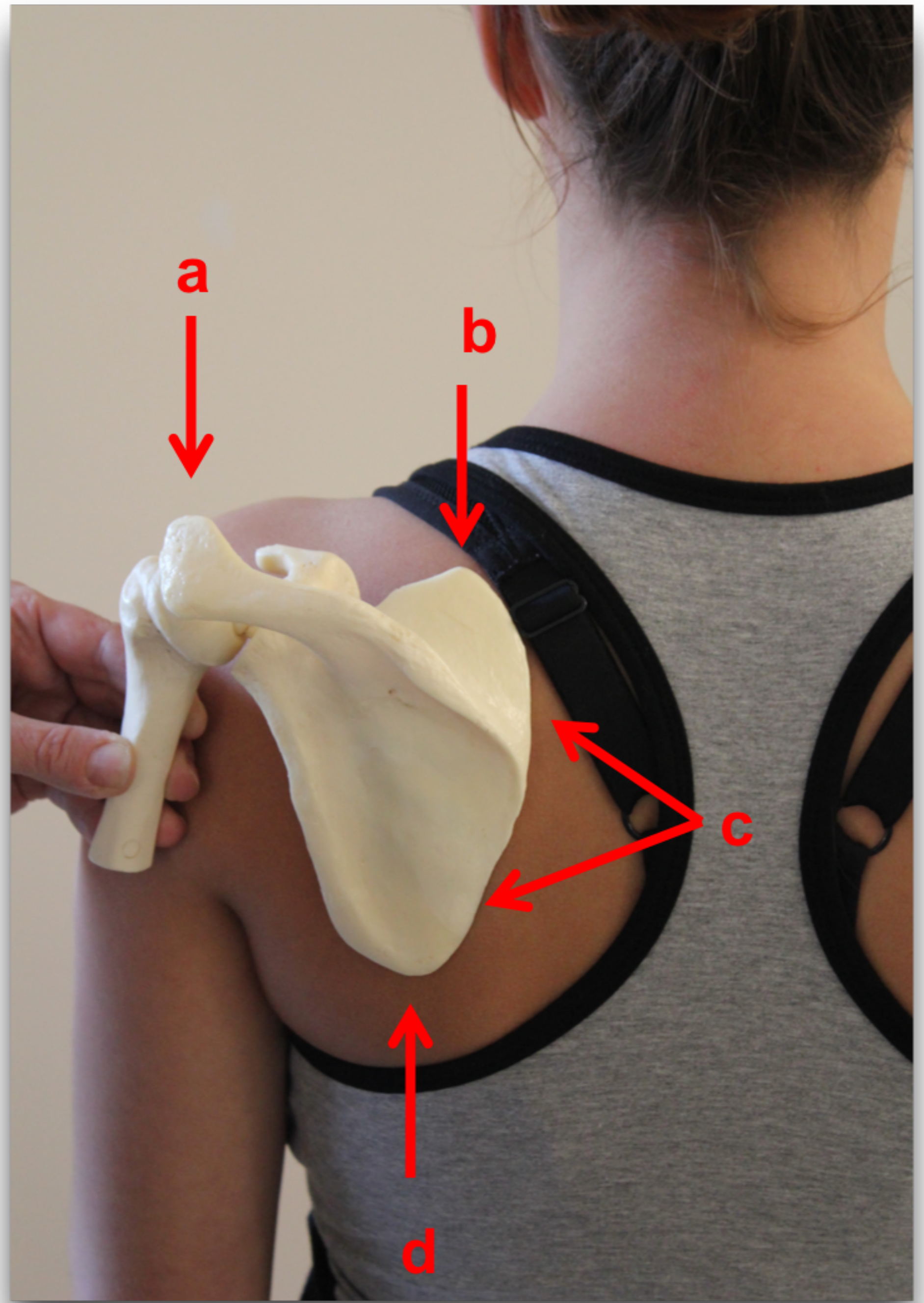

Figure 3.1 Key markers for assessing scapula orientation with arm by the side.

The scapula is between the ranges of upward and downward rotation (acromion (a) higher than superior-medial angle of the scapula (b)), external and internal rotation (medial border in contact with ribcage) (c) and posterior and anterior tilt (inferior angle in contact with ribcage) (d) (Mottram, 1997, Worsley et al., 2013).

3.1.2 Linking findings from anatomical morphometry study of Serratus Anterior to the action on scapula

The dissection study of serratus anterior identified subdivisions with distinctive attachment sites and fascicle angles (**Webb et al., 2018a**). The results suggest the subdivisions may have different actions on the scapula (Appendix D). The present author proposes:

- The upper division controls loss of movement choices (LMC) of site (scapula); direction, (downward rotation)
- The middle division controls LMC of site, (scapula) direction, (internal rotation/winging)
- Lower division control LMC of site, (scapula); direction, (downward rotation and retraction) (see **Figure 2.3**).

The orientation of the scapula with the arm by the side is the starting position for the cognitive movement control tests (CMCTs) at the scapula (**Mottram and Blandford, 2020**, Comerford and Mottram, 2012) and retraining strategies (Mottram, 1997, Struyf et al., 2013, Worsley et al., 2013) and is outlined in **Figure 3.1**. This concept developed from the clinical observation that individuals with neck and shoulder pain present with a LMC of site (scapula); direction, (downward rotation) on the Arm Flexion Test (4.3.1) (Mottram, 1997, Mottram et al., 2007, Comerford & Mottram 2012). A scapular orientation exercise has been described which aims to take the scapula from the clinically observed position of downward rotation to a mid-position (Mottram et al., 2007). The novel anatomy of the upper division, reported in the core anatomical study, identified a possible functional link to controlling the orientation of the scapula (**Webb et al., 2018a**). The vertically orientated short thick rib 1 and 2 fascicles potentially anchor the superior angle and contribute to controlling LMC downward rotation of the scapula.

The results from this study could inform movement retraining strategies to influence the recruitment of different subdivisions of serratus anterior and address specific sites and directions of LMC at the scapula, thus influencing orientation. In support, conscious control of the scapula (Mottram, 1997, Mottram et al., 2009b) has been shown to alter scapular orientation and muscle activation (Antunes et al., 2016, Worsley et al., 2013, Ou et al., 2016). Anatomical muscle morphometry is providing an insight into the potential functional roles which may direct training interventions (Kennedy et al., 2017, Assi et al., 2021, Storey et al., 2016).

As there are no current guidelines for electromyography (EMG) sensor placement for different subdivisions of serratus anterior, this research could inform on EMG electrode placement but would first need to be examined using fine wire electrodes to test this proposition.

3.1.3 Further study on Trapezius morphometry (paper in preparation)

To complement the serratus anterior project, a similar study was conducted on the trapezius muscle; aiming to quantify its morphometry (Bennett et al., 2015). Understanding the segmental actions may facilitate development of effective movement retraining strategies for the neck and shoulder. Methods, preliminary results and suggested actions are outlined in **Table 3-1**.

Table 3-1 Trapezius morphometry, methods, preliminary results and suggested actions (Bennett et al., 2015)

Trapezius
Methods: • Twenty trapezius muscles were dissected from 10 embalmed cadavers • Dimensions of the muscle and orientation of each fascicle was measured • Each fascicle was dissected to document its attachments and quantify fascicle length, thickness and volume, and to calculate the physiological cross-sectional area.
Anatomical findings: • Upper division (occiput to C6) fascicles, orientated 137°±12 to 93°±10 degrees to the spinous processes, attached to the lateral clavicle • Middle division (C7 to T2) fascicles orientated 90°±7 to 85°±9 degrees to the spinous processes, attached along the spine of the scapula • Lower division (T3 to T12) fascicles, orientated 75°±11 to 29°±10 degrees to the spinous processes, attached via a common tendon to deltoid tubercle • The middle division PCSA (3.71cm^2) was the largest, comprising 47% of total trapezius PCSA, compared to upper (1.71cm^2) and lower (2.55cm^2) divisions.
Proposed action: • Upper division: retraction of the clavicle • Middle division: upward rotation, internal rotation and posterior tilt of the scapula • Lower division: controls scapular elevation and provides an anchor at deltoid tubercle to facilitate upward rotation and posterior tilting.

3.2 Proof-of-concept case study illustrating movement analysis and electromyography during a cognitive movement control test

The second core paper is a proof-of-concept case study presenting validity of concept (**Mottram et al., 2019**). Pelvis and femur kinematics and EMG of tensor fascia lata (TFL) and rectus femoris (RF) were used as outcome measures during the Seated Hip Flexion CMCT pre- and post-cognitive movement retraining. Kinematic data revealed changes in pelvic movement pre-to-post intervention on the symptomatic side, (posterior tilt 11° to 6.5°, upward rotation (hitch) 5.2° to 3.2° and external rotation (anticlockwise rotation) 14.4°to 10.51°), which matched the focus of intervention (see 4.2.3). Range of hip flexion was similar pre-to-post illustrating that although the knee reached same place in space, the pattern of movement changed with less excursion of the pelvis. Onset timing of EMG of TFL and RF revealed muscle activation as delayed pre compared to post intervention. It could be hypothesised the hip flexor muscle synergies show changes in recruitment patterns to match the movement patterns of less pelvic movement and more hip flexion. These findings support the concept that cognitive movement retraining alters movement patterns, and these can be measured with EMG onset timing and kinematics as previously illustrated (Worsley et al., 2013) (see section 5.2).

3.3 Further publications, by the author of thesis, supporting kinematic and neurophysiological changes across different cohorts

This section presents further studies, illustrating kinematic and neurophysiological changes, associated with changes in MCS, across different cohorts.

Altered MCS have been reported in people with neck pain (Helgadottir et al., 2011, Helgadottir et al., 2010) and shoulder pain (Warner et al., 2015, Worsley et al., 2013) (Appendix C). Differences in scapular kinematics are seen in different cohorts (Warner et al., 2018) supporting the hypothesis that changes in MCS are associated with shoulder impingement syndrome presentations (SIS) (Appendix E).

Bracing and breath holding strategies are often observed during CMCTs (Comerford and Mottram, 2012). Roussel's study offers support for including the assessment of breathing patterns during CMCTs (Roussel et al., 2009a) (Appendix E).

Differences in MCS have been observed in people without shoulder pain as well as those with shoulder pain (Warner et al., 2015) (Appendix C). How these observations may influence risk of injury or performance needs further exploration. Athletes who developed shoulder pain, demonstrated significantly less upward scapular rotation at baseline than those athletes that remained pain-free (Struyf et al., 2014). Although this characteristic was not predictive of the development of shoulder pain, it does illustrate the potential importance of assessing not only the range of upward rotation but also the MCS associated with arm elevation.

3.4 Summary Chapter 3

This chapter provides evidence for anatomical and neurophysiological function, to support the scientific basis underpinning the assessment and retraining of MCS (**Webb et al., 2018a**, **Mottram et al., 2019**). The anatomical findings have informed retraining strategies and neurophysiological function has been seen to vary between different cohorts and to change with cognitive movement retraining. This evidence supports the design of assessment strategies to identify MCS, and retraining strategies to improve pain, function and quality of life. Chapter 4 utilises this knowledge to review assessment strategies to identify MCS.

Chapter 4 Assessment of Loss of Movement Choices using Cognitive Movement Control Tests

The concept within this thesis proposes the health of movement is influenced by movement coordination strategies (MCS) (**Figure 1.1**). This chapter uses three core publications to support use of cognitive movement control tests (CMCT's) to identify loss of movement choices (LMC) (**Figure 2.4**):

- The theoretical concepts (**Mottram and Blandford, 2020**)
- A reliability study of an assessment tool (**Mischiati et al., 2015**)
- A proof-of-concept case study (**Mottram et al., 2019**).

4.1 Development of concept for assessing for loss of movement choices with cognitive movement control tests

Assessment of MCS with CMCTs requires an individual to cognitively coordinate movement at a specific region (e.g., low back), in a particular plane of movement (e.g., flexion), while challenging coordination by producing movement at another joint segment to a benchmark standard (**Mischiati et al., 2015**, Wilson et al., 2018, **Mottram and Blandford, 2020**). These tests can be performed under low and high threshold loading (non-fatiguing alignment and coordination skills or fatiguing strength and speed challenges) during single and multi-joint movements (**Mischiati et al., 2015**). These clinical tools, using observational rating of movement, require subjective decision making by the therapist on the presence of 'observable' movement occurring at a specified test site (**Mottram and Blandford, 2020**); (e.g., is flexion observed at the low back?).

The timeline for the developments of CMCTs are outlined in Appendix B. The following sections detail scientific support for these tests.

4.2 Core publications supporting the reliability of cognitive movement control tests

4.2.1 Assessment of movement coordination strategies

The concept and assessment procedure for CMCTs within a clinical framework to evaluate LMC has been detailed (**Mottram and Blandford, 2020**) (**Figure 2.4**). Five CMCTs, assessing for the site, direction and threshold® of LMC were presented with reference to literature to support reliability and clinical utility (**Figure 2.3**) (**Mottram and Blandford, 2020**).

4.2.2 Intra and inter-rater reliability cognitive movement control tests (experienced raters)

The second core paper supporting this chapter, reported on reliability of CMCTs with experienced raters (**Mischiati et al., 2015**). The results demonstrated good inter-rater reliability, excellent intra-rater reliability but real-time versus video was moderate to poor (Appendix F). For example, results from criteria for Test 2d– 'can you prevent the weight bearing knee turning in across the foot to follow the pelvis as you turn the pelvis away from the standing foot?'; intra-rater reliability was 100% for both raters, inter-rater-reliability 92.5%, but real-time versus video was only 55%. This illustrates therapists moving around a room, assessing movement from a 3-D perspective, give differing results to a 2-D perspective (video recording). This is supported by results reporting differences in 3-D hip and knee kinematic profiles during a single leg squat, even among people that had similar 2-D frontal plane projection angles (Di Staulo et al., 2019).

4.2.2.1 Intra-rater reliability cognitive movement control tests (novice raters)

Results of a reliability study still in preparation (Mottram et al.) for two novice raters, evaluating the same video recordings of CMCTs used by Mischiati (**Mischiati et al., 2015**), show acceptable intra-rater reliability **Table 4-1**. There has been a rapid implementation of virtual clinics, since the outbreak of the COVID-19 pandemic, so establishing the reliability of virtual assessment methods has become urgent (Gilbert et al., 2020, Cottrell and Russell, 2020). Reliability of testing for LMC, by remote observations (video recordings), has been demonstrated (Mottram et al. in preparation) **(Mischiati et al., 2015**).

Table 4-1 Results of intra-rater reliability cognitive movement control tests (novice raters)

Virtual assessment of movement coordination strategies using cognitive movement control tests: intra-rater reliability of novice raters.

Mottram et al. (in preparation)

Methods: 20 university sports students performed tests and were scored by two novice therapists. Intra-rater reliability of 75 criteria from nine CMCTs from The Foundation Matrix movement screen.

Results: overall percentage agreements for both novice raters combined was 86%, (Rater 1 88%, Rater2 84%)

AC1 and Kappa range values for Rater 1 were, AC1 = 0.27-1.00, Kappa = -0.06-1.00 and Rater 2, AC1 = 0.01-1,00, Kappa = -0.05-1.00

ICC's for overall agreement were good for Rater 1 0.90 (95% CI: 0.76-0.96) and moderate for Rater 2 0.72 (95% CI: 0.41 – 0.88).

4.2.2.2 Statistical analysis of cognitive movement control tests

Mischiati et al. (2015) reported limitations using Cohen's Kappa coefficient despite it being widely used in observational studies to determine the reliability of measurements (O'Leary et al., 2014, **Mischiati et al., 2015**, Webb et al., 2018b). Kappa often applies a drastic correction for chance, particularly in cases where there are few agreements or many agreements between pairs (Grant et al., 2017), as seen in movement quality/screening tests (Whatman et al., 2012). Gwet's AC1 is chance-adjusted and as opposed to Kappa, uses average rather than individual marginal totals making it more robust with regard to extreme prevalence values (i.e., 0 or 1) (Whatman et al., 2012, Gwet, 2014, Grant et al., 2017). The data from the novice study supports the use of AC1 and the authors propose this is a more robust statistical tool for evaluating rater reliability (**Table 4-1**).

4.2.3 Proof-of-concept case report and use of The Foundation Matrix movement screen

The third core paper illustrates the use of The Foundation Matrix CMCT test battery, to identify LMC (**Mottram et al., 2019**) (**Table 1-1**). This paper illustrates how assessment findings, of LMC, can inform individualised retraining. Many exercise and neuromuscular retraining intervention protocols are targeted to the clinical condition (Griffin et al., 2018, Kemp et al., 2019), rather than to individual LMC, which may be a factor contributing to poor outcomes for conservative treatment.

4.3 Further relevant publications by the author of thesis supporting the use of cognitive movement control tests

4.3.1 The Arm Flexion Test

The CMCT (Arm Flexion Test) characterises the site and direction of LMC (**Figure 2.3**), at the scapula, and allows the clinician to reason the relevance of this to the presentation and direct retraining. (Comerford and Mottram, 2012, **Mottram and Blandford, 2020**). A review explored the relationship between shoulder SIS and scapular orientation and concluded there is insufficient evidence to support the clinical belief that the scapula adopts a common and consistent posture in SIS (Ratcliffe et al., 2014). A large-scale multi-centre randomised control trail (RCT), in progress, investigating exercise intervention for SIS and rotator cuff disorders excludes ‘isolated’ exercises to correct posture based on the conclusion of Ratcliffe, and focuses on exercises commonly used in clinical practice (Keene et al., 2020). The programme by Keene et al. does not address specific assessment or retraining of MCS. Appendix C sets out the body of work supporting the use of the Arm Flexion Tests, to identify LMC at the scapula, to direct intervention rather than observing posture alone.

4.3.2 Reliability of cognitive movement control tests in older people

Acceptable reliability has been established for CMCTs on older people (aged 65-85 years), both golfers and non-golfers (Rowsome et al., 2016, Webb et al., 2018b). These tests are designed to identify LMC relevant to typical everyday activities in the older population, for example sitting to standing, reaching.

There has been a recognition of the contribution of motor control and cognition in exercise interventions to reduce falls (Sherrington and Henschke, 2013, Liu-Ambrose et al., 2013). Motor learning exercise including balance and coordination, has improved walking, quality of life and cognitive function in older adults (Brach et al., 2013, Dunsky, 2019). As balance requires appropriate coordination and timing of muscle synergies, it may be of value to assess older adults for LMC. Identifying LMC, with a battery of CMCTs, specifically designed for the older person

(Webb et al., 2018b), may assist in the development of targeted cognitive movement retraining interventions to reduce the risk of falls and improve quality of life.

4.4 Other relevant publications supporting the concept

Two other publications reporting on CMCTs work are discussed below. An inter and intra-rater reliability study, using CMCTs on marines reported inter-rater reliability was moderate to excellent (Kappa 0.56-0.95) and intra-rater reliability was poor to moderate (Kappa 0.22-0.58) (Monnier et al., 2012). The intra-rater reliability, test-retest strategy, was to retest participants at 7 – 10 days, rather than using observation of video recordings as described by Mischiati (**Mischiati et al., 2015**). This could account for the poor Kappa scores compared to other studies as the marines may have been moving differently on second evaluation considering the constraints influencing movement (2.1.1). The CMCT only scored LMC at the low back, but these results suggest a battery of tests scoring LMC, including different sites and directions may be of value when exploring the specificity of CMCTs (Monnier et al., 2012).

A single case report has documented that observational ratings of LMC of the pelvis and hip in two CMCTs may be accurate, when compared with kinematics using 3D motion analysis (Wilson et al., 2018). The young ex-footballer, with low back and groin symptoms, performed the CMCT (small knee bend) pre- and post-movement control retraining. Pre intervention LMC was observed on the CMCT and noted as site (pelvis), direction (anterior tilt) (see **Figure 2.3**). Post intervention, this was no longer observed and pelvic anterior tilt had decreased by 16 -17° (kinematic data). These findings demonstrate proof-of-concept, that CMCTs can identify LMC, and established that LMC is sensitive to change following retraining. Movement retraining changed LMC and also led to a reduction in hip and groin symptoms adding to the proof-of-concept for effect of this type of training.

4.5 Movement screening

Identifying risk factors for musculoskeletal injury in the general population, sport and service-related occupations is a focus of research (Roos and Arden, 2016, Whittaker et al., 2017, Keenan et al., 2017).

A systematic review of 17 studies, reported inconsistent evidence that movement quality is associated with an increased risk of injury (Whittaker et al., 2017). Fifteen of the 17 papers reviewed, used the Functional Movement Screen (FMS) (Whittaker et al., 2017). It has been suggested that an individual with a total score of less than 14 out of 21 is more at risk of injury

(Kiesel et al., 2007). However, the present position suggests this cut-off point is not an effective strategy to subgroup athletes into high-risk and low-risk injury risk groups and questions the value of observation of movement patterns for assessing risk of injury (Moore et al., 2019, Trinidad-Fernandez et al., 2019, Whittaker et al., 2017).

Movement coordination strategies have been shown to be a risk factor in injury (Roussel et al., 2009b, Dingenen et al., 2015, Schuermans et al., 2017a, Rossi et al., 2020, Frank et al., 2019, Leppanen et al., 2020). However only Roussel used CMCTs to identify changes in MCS and reported that failing two low back CMCTs has been associated with an increased risk of developing lower extremity or low back injuries in dancers (Roussel et al., 2009b). This illustrates the potential value of CMCTs in injury risk management approaches and warrants further research.

4.5.1 Movement screening and The Performance Matrix

The Performance Matrix (TPM), an online movement analysis and risk reporting technology platform, uses a battery of CMCTs to identify LMC (Comera Movement Science, 2020c). The TPM system was invented by Mark Comerford and the author, and launched by Comera Movement Science in 2011, and was partially funded by Advantage Proof of Concept Fund (Advantage West Midlands and the European Regional Development Fund). The key features of TPM test batteries are outlined in **Table 4-2**.

Table 4-2 Key features of The Performance Matrix movement analysis and risk reporting tool

- Identifying LMC with CMCTs rather than observation of movement compensations
- Using functionally related multi-joint movement tasks, rather than single joint tests
- The Foundation Matrix includes generic rather that sport-specific tasks and can be applied to any sport (**Mischiati et al., 2015**)
- Sport and occupations-specific tasks matrices (e.g., The Football Matrix, The Golf Matrix, The Tactical Athlete Matrix)
- Identifying both low threshold (alignment and coordination) and high threshold (strength and speed) LMC
- A risk reporting algorithm details high and low risk LMC and assets, i.e., regions with no LMC which can be progressed more rapidly in training
- Detailing LMC attributes by site, direction and threshold® (Mottram and Comerford, 2008, **Mottram and Blandford, 2020**) (see **Figure 2.3**)
- The CMCTs are characterised by distinctive elements for each test; start position, test movement, end position and the benchmark standard (Comerford and Mottram, 2012, **Mischiati et al., 2015, Mottram and Comerford, 2008)**.

Some evidence is emerging to support the importance of exploring both low threshold and high threshold motor unit behaviour in painful conditions (Martinez-Valdes et al., 2020), which is a unique feature of TPM (**Table 4-2**). The observed increase in high threshold motor units is likely to be a response to the low threshold inhibition and allows the force output to be maintained but leads to fatigue and possible longer term altered motor unit activity and stress on muscle tissue (Martinez-Valdes et al., 2020).

4.5.1.1 The Performance Matrix, footballers and hamstring injuries

Ninety male elite professional footballers were screened with TPM's The Football Matrix. Each player reported history of injury(s). The results indicated: i) 99% of footballers failed tests at the low back and 79% demonstrated LMC site (low back), direction (extension) threshold (high), (see **Figure 2.3**), in the series of high threshold (strength and speed tests) (Comerford et al., 2011), and ii) hamstring injury was the second most common reported previous injury (20%). Loss of movement choices, site (low back), direction (extension), threshold (high), showed a significant association with a history of hamstring injury ($p>0.05$) (Mottram et al., in preparation) (Mottram et al., 2012a).

Preliminary studies suggest higher levels of neuromuscular control are linked to a reduced risk of hamstring injury and altered recruitment of low-back-pelvic musculature is associated with hamstring injury risk (Franettovich Smith et al., 2017, Schuermans et al., 2017b). This suggests addressing changes to MCS and synergistic contributions around the low-back-pelvic region to be a possible tool in management of hamstring injury risk (Blandford et al., 2018a). Testing for LMC, with a test battery of CMCTs e.g., TPM's The Football Matrix, has the potential to be used by practitioners to direct interventions to change MCS and target retraining of MCS (both joint and muscle synergy coordination).

4.5.2 The Hip and Lower Limb Movement Screen

The Hip and Lower Limb Movement Screen (HLLMS) has been designed to observe for movement quality to inform the design of exercise programmes to reduce injuries or prevent the progression of injuries to post traumatic osteoarthritis (Booysen et al., 2019). The HLLMS was developed to include a focus on hip and pelvic control that is lacking in the FMS. Intra-rater reliability has been reported as excellent for overall HLLMS (Booysen et al., 2019). Movement quality was observed when the athlete was asked to cognitively control movement to the benchmark.

A LMC is defined as an observed compensation, that is not able to be cognitively controlled, on achievement of a defined benchmark (**Mottram and Blandford, 2020**). It is not always clear, in studies using movement control tests, if methods match the protocols describing CMCT. For example, Tegern looked to report more on the observation of movement patterns rather than teaching individuals to cognitively control the movement to the required benchmark (Tegern et al., 2018). Whilst CMCT and observation of preferred movement patterns are useful clinical tools to assess the health of movement, it is necessary to report methods so future reviews can compare the two assessment systems.

4.6 Summary Chapter 4

This chapter has reviewed support for the use of CMCT to identify LMC. Three core papers illustrate: i) the theoretical concept for the use of CMTS to identify LMC (**Mottram and Blandford, 2020**); ii) the reliability of CMCTs (**Mischiati et al., 2015**); and iii) the clinical utility to identify LMC in an athlete which can inform a retraining strategy (**Mottram et al., 2019**).

In addition, support for the use of the Arm Flexion test has been presented, along with reliability of movement tests in older adults and marines, and a case study illustrating the accuracy of CMCTs.

The author considers the assessment of CMCTs to be the cornerstone of the concept, set out in **Figure 1.1**. Cognitive movement control tests reveal LMC and the results of the tests inform retraining. Cognitive movement retraining is set out in the next chapter.

Chapter 5 Cognitive Movement Retraining

This chapter explores the concept for cognitive movement retraining based on the classification of loss movement choices (LMC) identified with cognitive movement control tests (CMCTs) (Chapter 4). The clinical application of movement retraining interventions focuses on changing movement coordination strategies (MCS) by restoring LMC (**Figure 2.4**) and aims to improve the health of movement of an individual (**Figure 2.5**). Two core papers support this chapter:

- An original proof-of-concept case study illustrating how a retraining intervention can be tailored to an individual's presentation and findings on CMCTs to improve symptoms and movement control (**Mottram et al., 2019**) and
- A clinical reasoning framework, making the individual's health of movement status central (**Mottram and Blandford, 2020**).

Movement coaching is presented as a key element of movement retraining.

5.1 Core publication supporting cognitive movement retraining

Key work to support proof-of-concept is a case report (**Mottram et al., 2019).** Common in young and middle-aged adults, femoroacetabular impingement syndrome (FAIS) is a motion related condition of the hip (Griffin et al., 2016).

The results outlined in section 3.2, illustrate the effectiveness of matching the athlete's LMC, identified with CMCTs as site (low back/pelvis), direction (extension/anterior tilt) (**Figure 2.3**) to symptoms (hip pain) and loss of performance (rowing). Prioritising the LMC to the individual's goals can shape an effective and efficient individualised movement retraining programmes (**Mottram et al., 2019**).

Despite these observations there is little reported evidence to suggest that retraining MCS in individuals with femoroacetabular impingement syndrome (FAIS) is standard practice. Short-term outcomes of operative versus non-operative care for FAIS demonstrate both interventions produced positive outcomes, although surgery appears to be a superior option (**Mottram et al., 2019**, Dwyer et al., 2020). Reporting short-term outcomes only is a limitation as an association has been established between signs of FAIS, (particularly morphological abnormalities) and the development of osteoarthritis (Agricola R, 2016, Wyles et al., 2017).

Evidence suggests non-surgical intervention, including strengthening, neuromuscular exercise and improving flexibility, may hold some value in the management of FAIS (McGovern et al., 2019, Hoit et al., 2019, Kemp et al., 2020). However, further work is needed to provide high quality, outcome driven exercise therapy programmes (Kemp et al., 2019). The author of this thesis believes no other studies to date specifically assess for LMC to drive individualised movement retraining for FAIS. This proof-of-concept case study puts forward the case for testing for LMC to direct individual retraining and improve pain, function and return to sport (**Mottram et al., 2019**).

5.2 Further relevant publications by the author of thesis

Retraining the orientation of the scapula was the basis of the retraining protocol for two publications exploring the effect of scapular focused movement retraining for SIS (Worsley et al., 2013) (Appendix C).

A review reports exercise is strongly recommended in the management of SIS but ongoing and future research to provide guidance of exercise type dose and duration is required (Pieters et al., 2020). One exercise/protocol has not shown to be more effective which probably reflects the numerous constraints influencing movement in an individual (see section 2.2). Consideration of using MCS as an assessment and outcome measure may help to direct individualised interventions.

5.3 Clinical reasoning

The concept in this thesis is to improve the health of movement by influencing MCS, rather than on treatment approaches for different aspect of the presentation or constraints (see section 2.1.1). A clinical reasoning framework, making the individual's health of movement status central, has been detailed in one of the core papers (**Mottram and Blandford, 2020**). The following sections explore some aspects of this clinical reasoning process.

5.3.1 Evidence-based health care

The introduction of evidence-based health care has helped direct clinical interventions. However, whilst randomised control trials show the average treatment effect, they do not consider the complex interactions of domains and comorbidities seen in clinical practice, or reflect judgement of clinical expertise (Low, 2020).

A person-centred approach is needed in the clinical reasoning process, making the individual's narrative central, whilst supported by population data, clinical research, policy and guidelines (Low, 2020). Kerry advocates the therapist and individual engage in a multi-dimensional clinical reasoning framework to explore how causal partners, (i.e., factors in all domains in section 2.1.1), influence the effect, e.g., MCS (Kerry et al., 2020). This thinking is based on dispositional philosophy of science and proposes causes are not discrete regularities, but rather real features that only ever tend towards an effect and are dependent on the mutual manifestation with other causal partners (Kerry et al., 2020). Clinical reasoning encompasses clinical expertise.

5.3.2 The biopsychosocial model and negative feedback model

It has been contended that a coherent biopsychosocial model is lacking, that links the biological, psychological and social factors reflected within an individual, and a mechanism of negative feedback has been proposed to allow for a model to be developed (Carey et al., 2014). A negative feedback mechanism may influence choices in MCS. Constraints outlined in the domains in **Figure 2.2** may interact and disrupt the negative feedback and consequently LMC arise. This supports Kerry's theory of reconceptualising causation in dispositionist terms for a more person-centred, multidimensional clinical reasoning process (see section 5.3.1) (Kerry et al., 2020). The status of the health of movement of an individual is not static, and effect of causes/constraints are ever-changing the status.

5.3.3 Clinical reasoning and the health of movement

A clinical reasoning approach, considering the relationship between the health of movement and LMC, allows for individual uniqueness, adaptation of interventions to account for influences of different domains and consideration of theoretical and mechanistic knowledge (Chapters 2 & 3). The clinical reasoning framework previously reported (**Mottram and Blandford, 2020**), has been expanded in this thesis to include how the health of movement can be influenced not only by constraints but by an individual's will and ability to act upon their feelings and desires (**Figure 5.1**). This respects the interaction of causal factors to influence MCS, and the health of movement. Assessment of MCS allows the therapist to consider the influence of causal factors on movement outcomes. Movement retraining can influence many causal factors at the same time and puts the focus on changing MCS rather than 'treating' individual constraints. The inextricable link between mental health, well-being and movement dictates the need for patient centred clinical reasoning. Promoting and fostering mental health and resilience is part of the cognitive movement retraining pathway and involves mindful strategies (Appendix G).

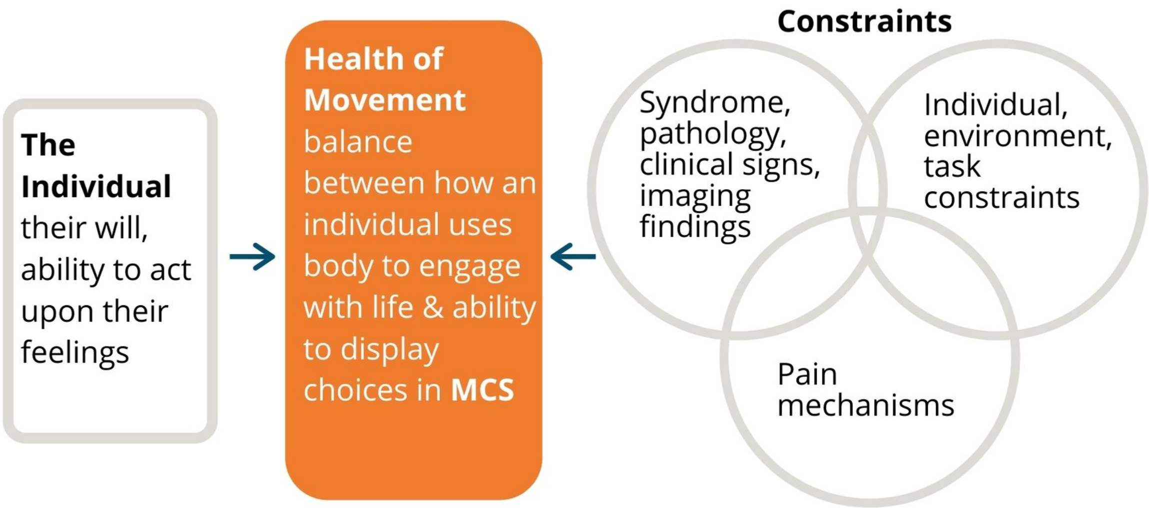

Figure 5.1 Clinical Reasoning and Health of Movement: A person-centred approach making the individuals narrative central

5.3.4 Reflective practice

Central to developing a clinical reasoning process and movement coaching skills is reflective practice. Reflecting on the immediate effect of a range and variety of cueing and facilitation strategies, (e.g., sensory input on disrupting negative feedback influencing MCS (see section 5.3.2), may build confidence in applying movement retraining. The practitioner is involved in skill acquisition along with the individual e.g., by enhancing their perceptual skills and expanding cueing strategies. Artistry has been defined as reflection-in-action, witnessed day to day in circumstances unique or uncertain (Schön, 1994). Perhaps movement retraining is an art as well as a science, as the practitioner adapts to the effect of the causal partners influencing MCS and the practitioner's influence on movement coaching maybe a causal factor (see section 5.3.3).

5.4 Movement Coordination Strategies and Pain

A theory for explaining motor adaptation to pain proposed redistribution of activity within and between muscles with changes at multiple levels of the motor system (Hodges and Tucker 2011). This response to pain has short-term benefits, at the time of injury, such as changing load and responding to the injury threat. A potential long-term consequence is decreased coordination variability (Hamill et al., 2012) (see section 2.1.1). Changes in MCS are observed in experimentally induced pain (Madeleine et al., 2008, Muceli et al., 2014) and clinical presentations (Worsley et al., 2013, Claus et al., 2018). The assessment protocol for evaluating MCS is outlined in Chapter 4 is proposed as a clinical tool to assess for reduced coordination variability (see section 2.2.2). Changes within the brain are observed in people with pain and following injury (De Pauw et al., 2019, Kregel et al., 2015, Baumeister et al., 2008, Shanahan et al., 2015) and may influence MCS (De Pauw et al., 2019). A clinical assessment framework using CMCTs to question reduced coordination variability is described in one core paper (**Mottram and Blandford, 2020**) (see section 2.2.2).

5.5 Muscle Synergies

This thesis, so far, has focused one element of MCS, intersegmental coordination evaluated with CMCTs. However, coordination also refers to the muscle synergy coordination (**Mottram and Blandford, 2020**, Hug and Tucker, 2017) (**Figure 2.1**).

On performing a task, the central nervous system (CNS) has to manage the number of degrees of freedom of the neuromuscular system (Bernstein, 1967) and motor abundance (Latash, 2012). The CNS is thought to manage this complexity of movement by using sets of muscle groups known as muscle synergies (Sharif Razavian et al., 2019). This patterning of muscles can help distribute mechanical stress in tissues (Hug and Tucker, 2017). However, motor adaption to pain and the reorganisation of muscle synergies may lead to ongoing tissue stress (Hamill et al., 2012) (see section 5.4). A systematic review has reported consistent evidence for differences in muscle synergies between individuals with and without musculoskeletal pain (Liew et al., 2018).

The analysis of the motor adaptation response of muscle synergies to pain (see section 5.4), in musculoskeletal conditions, is relatively new (Liew et al., 2018). Motor adaption to pain has been investigated in individual muscles and recruitment characteristics have been shown to change in the presence of pain and history of pain (Blandford et al., 2018b, Muceli et al., 2014, Heales et al., 2016). Exploring responses of individual muscles provides an insight to motor adaptation but it does not examine the complexity of movement within the CNS and possible changes within muscle groups/synergies.

The motor adaptation response of one or several muscles or synergistic groups can be accompanied with changes in MCS (Worsley et al., 2013, Lopes Ferreira et al., 2020, Mottram et al., 2019). Scapular downward rotation on kinematic analysis was accompanied with changes in neural recruitment of serratus anterior and lower trapezius muscles, providing support for the assessment of MCS to infer upon changes in relevant muscle recruitment strategies (Worsley et al., 2013) (Appendix B). Identifying the site and direction of LMC guides this decision making and can direct the therapist to focus on the muscles that eccentrically control the site and direction of

LMC (**Mottram and Blandford, 2020**). The core publication (**Mottram et al., 2019**) gives support for the use movement retraining to change muscle recuitment.

Assessment of MCS is supported by the current understanding of how the brain's cortex encodes movement sequences, by using muscle synergies as a way of translating cortical commands into specific muscles activities (Maguire et al., 2019); thus goal-focused testing of MCS may inform muscle synergies. To date research has reported on the relationship between kinematic data and muscle synergies (Gizzi et al., 2015, Lopes Ferreira et al., 2020) but not on the relationship between CMCTs and muscle synergies. This may give further insight into the role of assessment of MCS to direct rehabilitation.

5.6 Cognitive movement retraining and movement coaching

The core paper (**Mottram and Blandford, 2020**) outlines the aim of cognitive movement retraining to restore LMC (access motor abundance) by restoring coordination variability. The core publication, proof-of-concept case study, (**Mottram et al., 2019**) supports the use of cognitive movement retraining to restore LMC and reduce pain and improve function. Additional support for retraining coodination variability to change pain is supported in section 4.4 (Wilson et al., 2018) and section 5.2 (Worsley et al., 2013).

Altered network properties in people with chronic neck pain compared to healthy controls and altered MCS measured with the craniocervical flexion test has been reported (De Pauw et al., 2020). This evidence suggests movement retraining strategies targeting cognitive elements may be crucial in the management of people with chronic pain to enhance motor learning and recovery of LMC.

Retraining MCS to restore LMC requires a change or transformation in motor planning. Three progressive phases of learning a new skill have been described (Fitts and Posner, 1967); cognitive phase, understanding of the required action; associative phase, practice of the programme learned in the cognitive phase; and autonomous phase, during which the performer learns to carry out the skill with little conscious effort. During the early phases of motor learning conscious control is associated with restricting joint ranges of motion and tightly coupling of the motion of different joints (Bernstein, 1967; van Ginneken et. al., 2018). This is implemented by retraining simple, single plane MCS. As learning progresses in the associative phase, the movements can be made more complex and include intersegmental and multi-planer tasks (Worsley et al., 2013; **Mottram et al., 2019**). A rehabilitation programme, focusing on progressive intersegmental control, illustrates biomechanical changes in a cutting manoeuvre in the autonomous phase (King et. al., 2018). Skill acquisition (autonmous phase) may involve the freeing and development of functional couplings between degrees of freedom in movement, which requires access to redundancy in degrees of freedom and coorindation variability (Gray, 2020). This supports the aim of cognitive movement retraining to restore LMC (access motor abundance) by restoring coordination variability.

The premise is movement retraining is not just an exercise prescription but an approach to changing how people move in the long term through altering MCS. The therapist, collaborating with the individual, becomes a facilitator of learning (movement coach). Key elements central to the authors movement coaching practice are outlined in Appendix G, and Appendix H outlines some practical strategies to alter MCS.

5.7 Summary Chapter 5

This chapter presents evidence to support the clinical application of movement retraining interventions, focusing on restoring movement choices. A proof-of-concept case study has illustrated a positive effect of retraining tailored to the individual (**Mottram et al., 2019**) and support for this concept strengthened with additional publications by the author of this thesis. A person-centred clinical reasoning framework has been presented to allow for consideration of causal factors on movement outcomes, with a focus on changing MCS rather than ‘treating’ individual constraints (**Mottram and Blandford, 2020**). Movement coaching is presented as a key element of movement retraining. Chapter 6 will explore the significance, implementation and impact of this work.

Chapter 6 General Discussion - The Health of Movement: Significance, Implementation and Impact

The fundamental elements of restoring movement choices in individuals for long-term health ASSESS, INTERPRET and RESTORE, are illustrated in an infographic (**Figure 6.1**) and have been argued in Chapters 2 – 5. This chapter sets out:

- To illustrate the significance of this concept
- To demonstrate how strategies to change the health of movement have been implemented to explore the impact of this concept.

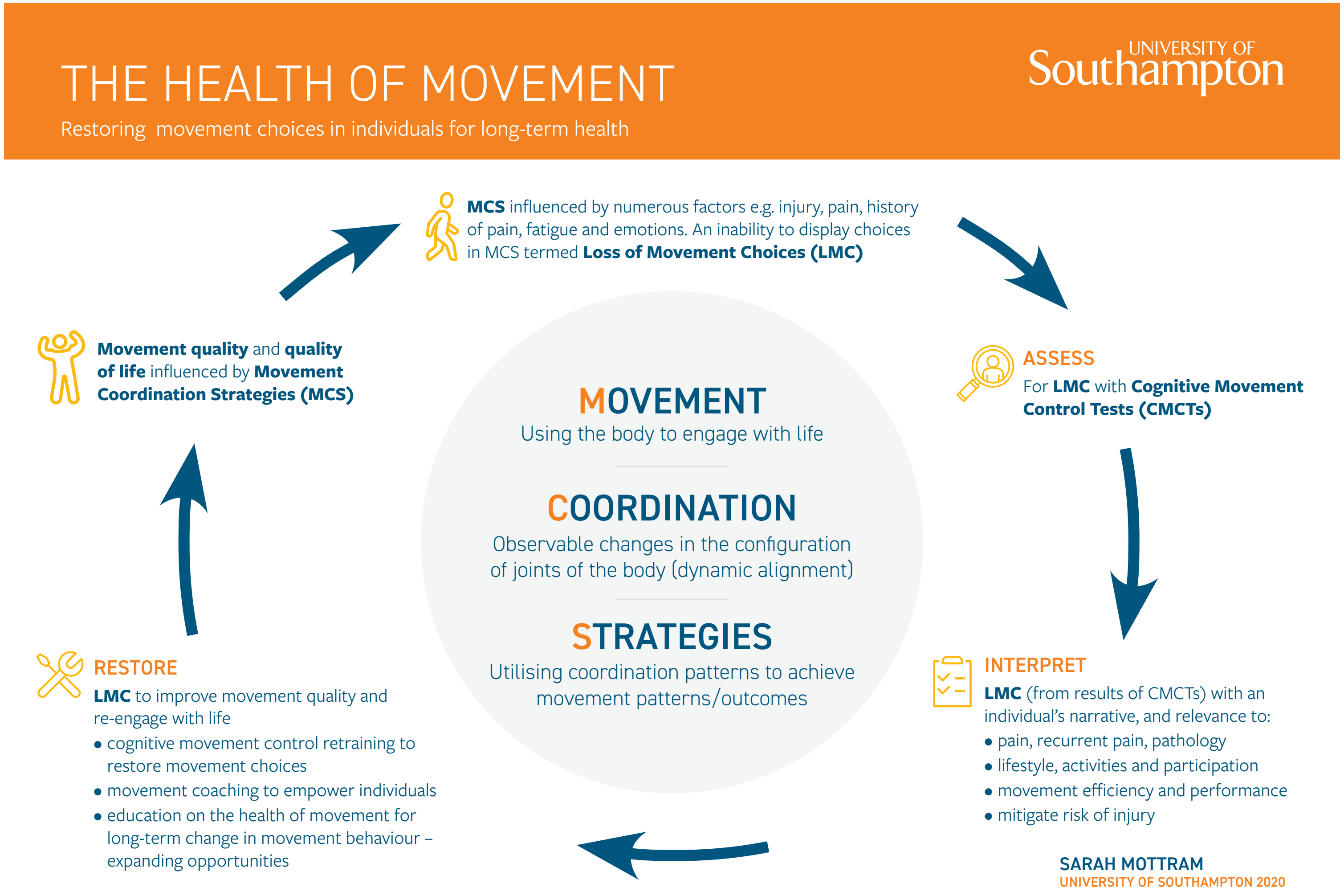

Figure 6.1 Infographic: the path of restoring movement choices in individuals for long-term health

6.1 Significance

The development of the clinical reasoning framework to assess and retrain movement coordination strategies (MCS), detailed in Appendix B, highlights novel features including:

- Development of an assessment strategy using cognitive movement control tests (CMCTs) to identify loss movement choices (LMC), and consideration of these findings within a clinical reasoning framework on an individual's health of movement
- Development of an approach for the observational rating of MCS. Use of these objective measures of LMC:
    - With people in pain, to drive rehabilitation strategies
    - In individuals without pain, to drive retraining strategies to improve performance and mitigate risk of injury
- As a tool to evaluate and manage the health of movement across a lifespan
- Development of single and multi-joint tests for each site, direction and threshold® of LMC.

6.2 Implementation

The research activities outlined in the thesis have illustrated that LMC can be:

- Identified by testing MCS with CMCTs
- Measured objectively with an observational rating method
- Used to design retraining activities to manage pain and improve function.

Figure 6.2 illustrates that this framework has been taught to therapists internationally, by a network of Comera Movement Science Accredited Tutors. The educational framework has enabled the author and the Comera Movement Science to grow a global community of therapists (Kinetic Control Movement Therapists) to empower people to manage their own movement health (Comera Movement Science, 2020b). The author of this thesis has presented at international conferences and taught over 1000 days on assessment and retraining of LMC, in 20 different countries (Comera Movement Science, 2020d).

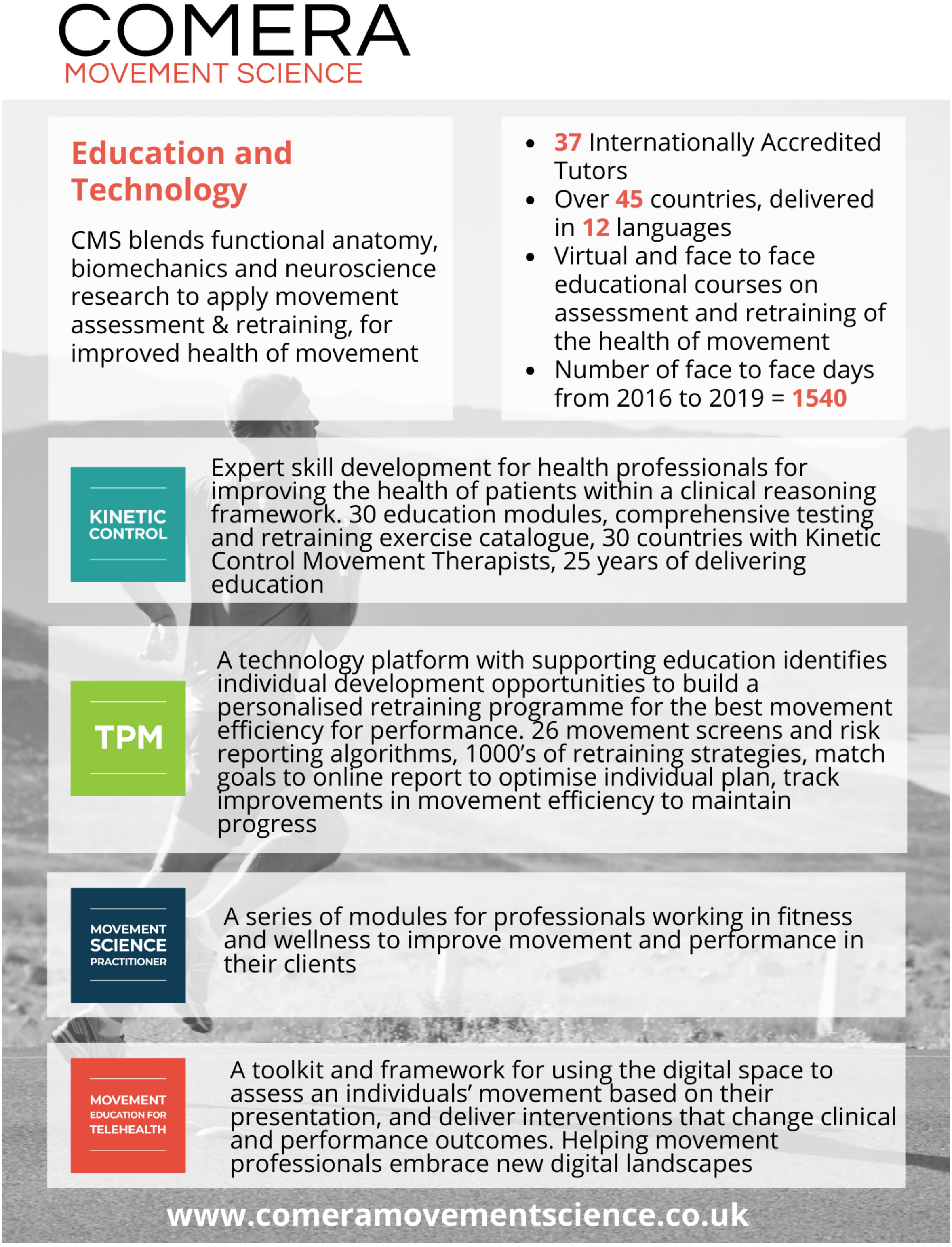

Figure 6.2 Comera Movement Science

Examples of education and technological developments using the concepts within this thesis (Comera Movement Science, 2020a).

6.2.1 Implementation of The Performance Matrix

One development resulting out of the unique features described in section 4.5.1 was The Performance Matrix (TPM) (**Figure 6.2**). Features are outlined in **Table 4-2**, and TPM has been used worldwide in different settings and populations including:

- Identifing possible risk factors in different groups to direct retraining (e.g. 3 year project with Royal Berkshire Fire and Rescue , contributed to less days lost from sickness (RBFRS, 2015, RBFRS, 2017))
- Identifying LMC as a possible risk factor to injury in elite sport and use in professional football (**Mottram et al., 2019**, Southampton Football Club, 2019)
- In clinics and wellness centres to manage clinical and performance presentations (Comera Movement Science, 2019, Body Logic Health, 2020).

6.3 Impact

6.3.1 Moving towards a holistic approach

The last 25 years has seen a general shift to a more holistic approach in Physiotherapy (see section 5.3). The significance and implementation of the concepts within this thesis, has contributed to this change (**Figure 6.2**). The observational assessment of MCS gives therapists a means to evaluate the influence of numerous constraints on movement outcomes (see section 2.1). The assessment tools can be used as outcome measures to evaluate interventions (Wilson et al., 2018).

6.3.2 Quotes and testimonials

Appendix I illustrates how the concepts presented in this thesis, including movement coaching from the author and CMS's educational and technology, has impacted individuals.

6.3.3 Scopus impact

Citations to date of published work is 1262 and illustrated in Appendix A (Scopus, 2020). The masterclass 'Dynamic Stability of the Scapula' (Mottram*, 1997)* has been cited 162 times. The scapula orientated exercise (SOE) described in the masterclass has been described in detail (Mottram et al., 2009b, Mottram and Comerford, 2008). Research protocols have referenced this work and adopted the SOE protocols (Kim et al., 2019, Wegner et al., 2010, Gutierrez-Espinoza et al., 2019).

6.4 Barriers to implementation

Some barriers to implementation are explored in this section.

6.4.1 Investment: time and money

The broad skills required to retrain movement are illustrated in Chapter 5. The investment in terms of time and money can be a barrier to the therapist and provider, particularly in relation to acquiring the skills of movement coaching, along with the understanding of value this can bring individuals in both the short and long-term.

6.4.2 Adding movement retraining and exercise to existing skill set

An observational study on the range of musculoskeletal therapies applied by manual therapists to patients with non-specific neck pain reported only 15.1% used exercise (compared to manipulation 33.8% and mobilisation 27.9%) and 0.4% used exercise as a standalone modality (Peters et al., 2020). This suggests this cohort of therapists have yet to fully realise the value of exercise as a modality or have depth of proficient skills to enable them to utilise exercise in a therapeutic way.

6.4.3 Communicating message through digital media

On reflection, the concepts within this thesis have not been broadly disseminated through digital communication. It is now time to communicate the importance of managing LMC, within different cohorts to clinicians and policy makers. Embracing the digital innovations of multimedia creation and social media dissemination is an important element of knowledge transfer (Barton and Merolli, 2019).

6.4.4 Adherence

Barriers to exercise for an individual include lack of motivation, time, physical environment and lack of supervision/monitoring (Moore et al., 2020). Results of a longitudinal study showed despite a focus on individualised programmes some barriers to adherence remained at 12 months, but concluded a strong therapeutic alliance appeared to facilitate adherence to exercise and physical activity (Moore et al., 2020). This supports the need to consider movement coaching as an important part movement retraining (Appendix G).

6.5 Next steps

The important next step in knowledge transfer (KT) is taking evidence to support the concept in this thesis to a wider audience. This includes:

- Embracing of digital innovations for dissemination (Barton and Merolli, 2019):
  - multimedia creation: illustrated in an international consensus on golf and health demonstrating how infographics and digital resources can be used in KT (Murray et al., 2018)
  - social media dissemination: Kinetic Control has 8,305 followers on Facebook social media channels can be a route for KT (Kinetic Control, 2020).
- Targeting different groups:
  - the end-users in understanding how movement quality can affect their life
  - health and wellness professionals in seeing the value of assessing and retraining LMC
  - decision makers in sport and occupational settings in gaining knowledge in how movement quality and LMC can influence performance and risk of injury
  - policy makers in health in reconsidering the influence of movement quality and LMC on health in general and quality of life
  - focus of different sports and occupations (e.g., golf, running, cycling, tactical athletes)
  - maintaining independence and reducing the risk of falls in older adults.

6.6 Summary Chapter 6

This chapter has illustrated the significance of the concept in this thesis, of assessing for and retraining LMC and examples of implementation and impact. The global reach of the theoretical concepts, education, and technological support to evaluate and change MCS demonstrates value for both the clinician and individual who are striving to improve the health of movement. The next chapter concludes the thesis.

Chapter 7 Conclusions and Recommendations

7.1 Movement transforms individual lives

The current PhD showcases how 25 years of clinical experience, research activities, education and technological innovations and application of movement methods, have shaped the concept set out in this thesis, which is: evaluating movement quality, specifically movement coordination strategies (MCS), and restoring loss movement choices (LMC), improves an individuals' coordination variability, affords a more robust movement system and ultimately improves the health of movement.

The aim of this thesis has been to detail the concept that assessing and retraining MCS may improve the health of movement. The presentation of theoretical concepts and research provides evidence for proof of concept and the validity and reliability of assessment procedures. The five core published works in this PhD have included:

- Two theoretical papers setting out the concept for assessing and retraining MCS and outlining the clinical reasoning framework to drive transfer into practice (**Mottram and Blandford, 2020, Dingenen et al., 2018**)
- One reliability study establishing the robustness of a movement quality assessment tool (**Mischiati et al., 2015**)
- A proof-of-concept case report demonstrating validity and proof-of-concept **(Mottram et al., 2019**)
- A dissection study of the morphometry of serratus anterior illustrating knowledge of the anatomical architecture can inform retraining strategies (**Webb et al., 2018a**).

As the thesis does not present a clinical trial, the effectiveness of this approach in improving the health of movement remains unknown.

Other research demonstrating changes in MCS has been reported and is supported with measures of altered kinematics (joint coordination) and intermuscular coordination (relative contribution of muscle synergists). This research has studied healthy people, people with pain and activity and participation limitations, youth to older people and people across the activity spectrum from less active to elite sports men and women.

The main body of the commentary has included chapters that provide insight into:

- **The health of movement:** exploring the relationship of how an individual uses their body to engage with life and the ability to display choices in MCS; the clinical relevance of this concept has been discussed throughout

- **The scientific basis underpinning measures of function and impairment**: laboratory measures of anatomical and neurophysiological function have been shown to inform assessment and retraining methodologies

- **The assessment of loss of movement choices with cognitive movement control tests (CMCTs):** an observational assessment of movement quality has been presented. The rationale for the use of CMCTs to evaluate LMC has been proposed; along with support for this being a feature of clinical presentations. LMC have been defined by their attributes of site, direction and threshold ® (**Figure 2.3**). CMCTs can be used as outcome measures, both for the individual to track clinical progress and as a research measure

- **Movement retraining**: Building a movement profile allows the therapist to interpret LMC in respect to the narrative, presentation and goals of the individual to direct retraining. A person-centred clinical reasoning framework has been presented, which enables the therapist to reflect on how the numerous constraints affecting movement interact with the individual and influence the health of movement. A holistic approach to retraining movement has been presented through movement coaching, building awareness and focused attention, to empower individuals to recognise and improve the health of their movement

- **Significance, implementation and impact:** illustrating the global reach of the theoretical concepts, education, and technological developments that have evolved out of the concept.

7.2 Recommendations

7.2.1 Restoring the Health of Movement

Movement provides individuals with possibilities of engaging with life, be it independence, interacting with family, gardening and social activities, exercise or amateur and elite sport. Increasing and maintaining physical activity is a key factor for a healthy life. Improving the health of movement by restoring MCS has the potential for people to access better health by allowing them to move better. This thesis recommends the assessment of MCS to guide retraining to improve the health of movement.

The author has proposed three essential elements central to optimising the health of movement: **ASSESS**, **INTERPRET** and **RESTORE** (**Figure 6.1**). The transfer of this 'know how' to health and wellbeing professionals can enable them to identify and retain LMC in individuals for short and long-term improvement in the health of their movement. This can integrate with other interventions targeting individual constraints.

7.2.2 Future research

Improving the health of movement by restoring MCS has the potential for people to access better health by allowing them to move better. The author's research journey will continue, with a particular interest on practical tools for assessment and how an individual's narrative can be the driver for individualised movement coaching. Further research to support the concept may include:

- Validity of CMCTs including The Performance Matrix Screening System
- Retraining of LMC to mitigate the risk of injury
- RCTs with economic evaluation
- Qualitative research to understand the therapist/patient experience of the approach.

This work will help inform further research to investigate the effectiveness of the concept on improving the health of movement.

7.3 Will you commit to the 'Health of Movement' movement?

There has never been a more important time in global history for championing the health of movement across countries, cultures and lifespans. The current health, social and economic state, has made individuals, health and wellness professionals, politicians and change makers value movement more than ever. Now is the time to transition to a more holistic approach to the health of movement and embrace individuals' narratives to enable them to steer their life course by giving them the best options to move. Identifying and changing LMC offers both practitioners and individuals the power to transform the health of movement. Addressing the dynamic state of the health of movement to change how people engage with life, is for all, whether they are 8 or 98 years old, from those with a sedentary lifestyle, the active and wellness minded to elite athletes.

Movement is problem solving. A robust movement system offers flexible problem solving for the individual and movement choices for each unique functional challenge. Will you be a force for change and take action to embrace the health of movement?

My vision and passion are to enable movement professionals, in both the health and wellness sectors, to empower every individual they work with to improve and maintain the health of their movement. Healthy movement allows individuals to engage with life, for quality of life, and a lifetime of activity, performance and participation.

Appendix A Publications by the Author

Contribution, by author of thesis, to 31 publications (including 5 core publications) and Scopus citations (Scopus, 2020).

Publication	Original contribution by S Mottram to publications	Scopus Citations
Core Publications		
1. Dingenen, B., Blandford, L., Comerford, M., Staes, F. & **Mottram**, S. **2018**. The assessment of movement health in clinical practice: A multidimensional perspective. *Phys Ther Sport*, 32, 282-292.	Conceptualisation of masterclass, establishing team, theoretical developments of model, assessment of movement in clinical practice; content and concepts overview, writing input into first draft (40%), review and editing.	13
2. Mottram, S. & Blandford, L. **2020**. Assessment of movement coordination strategies to inform health of movement and guide retraining interventions. *Musculoskelet Sci Pract*, 45, 102100.	Conceptualisation of masterclass, presentation of concept of assessment of movement coordination strategies, with cognitive movement control tests, to guide cognitive movement retraining. Writing of first draft (65%) and revision of manuscript (95%).	2

Publication	Original contribution by S Mottram to publications	Scopus Citations
3. Mottram, S., Warner, M., Booysen, N., Bahain-Steenman, K. & Stokes, M. **2019**. Retraining in a female elite rower with persistent symptoms post-arthroscopy for femoroacetabular impingement syndrome: a proof-of-concept case report. *J. Funct. Morphol. Kinesiol*, 4(2), 24.	Conceptualisation of case study. Design of experiment and methodology. Practical application of experiment including Retraining of athlete. Interpretation of results Writing of first draft (95%) and revision of manuscript.	2
4. Webb, A. L., O'Sullivan, E., Stokes, M. & **Mottram, S**. **2018**. A novel cadaveric study of the morphometry of the serratus anterior muscle: one part, two parts, three parts, four? *Anat Sci Int,* 93**,** 98-107.	Conceptualisation of research project. Contribution to design and methodology. Interpretation of results. Writing, contribution to first draft (40%), particularly background, interpretation and the functional role of the subdivisions, and revision of paper.	0
5. Mischiati, C., Comerford, M., Gosford, E., Swart, J., Ewings, S., Botha, N., Stokes, M. & **Mottram, S**. **2015**. Intra and inter-rater reliability of screening for movement impairments: movement control tests from the foundation matrix. *J Sports Sci Med*, 14, 427-40.	Conceptualisation of research project hypothesis and establishing collaboration with University of Chichester. Design of experiment, and methodology. Contribution to resources, data collection, data analysis and interpretation. Writing -input into first draft 40%, and revision of the manuscript.	15

Publication	Original contribution by S Mottram to publications	Scopus Citations
Textbook		
Comerford M, **Mottram S**. Kinetic Control, The Management of Uncontrolled Movement. Australia: Churchill Livingstone **2012**.	Concept design with Elsevier. Contribution to all chapters. In particular Chapters; 1 (concept and clinical reasoning); 4 retraining; and 5 shoulder tests, and the scientific support for concepts.	-
Other Publications		
Booysen, N., Wilson, D., Lewis, C.L., Warner, M.B., Gimpel, M., **Mottram, S**, Comerford, M.C., Stokes, M.J. **2019.** Assessing movement quality using the hip and lower limb movement screen: development, reliability and potential applications. *Journal of Musculoskeletal Research*, 22.	Concept of movement assessment with cognitive movement control tests. Application of test procedure. Revision of manuscript.	0
Botha, N., Warner, M., Gimpel, M., **Mottram, S**., Comerford, M. & Stokes, M. 2014. Movement patterns during a small knee bend test in academy footballers with Femoroacetabular impingement (FAI). Working Papers in Health Sciences 1, 1-5.	Concept of movement assessment with cognitive movement control tests. Application of test procedure. Revision of manuscript.	-

Publication	Original contribution by S Mottram to publications	Scopus Citations
Comerford, M., **Mottram, S**. **2001.** Movement and stability dysfunction--contemporary developments. *Man Ther,* 6, 15-26.	Conceptualisation. Building scientific rationale for the concept. Writing – original draft 50%, Writing – review & editing.	189
Comerford, M., **Mottram,** S. **2001.** Functional stability re-training: principles and strategies for managing mechanical dysfunction. *Man Ther* 6, 3-14.	Conceptualisation. Building scientific rationale for the concept. Writing – original draft 50%, Writing – review & editing.	132
Helgadottir, H.; Kristjansson, E.; **Mottram, S**., Karduna, A., Jonsson, H., Jr. **2011**. Altered alignment of the shoulder girdle and cervical spine in patients with insidious onset neck pain and whiplash-associated disorder. *J Appl Biomech,* 27, 181-191.	Concept of movement impairment and how this affects clinical presentation of people with neck pain and significance on their health. Assessment strategies. Writing – review & editing.	25
Helgadottir, H.; Kristjansson, E., **Mottram, S**., Karduna, A.R., Jonsson, H., Jr. **2010.** Altered scapular orientation during arm elevation in patients with insidious onset neck pain and whiplash-associated disorder. *J Orthop Sports Phys Ther*, 40, 784-791.	Concept of movement impairment and how this affects clinical presentation of people with neck pain and significance on their health. Assessment strategies. Writing – review & editing.	34

Publication	Original contribution by S Mottram to publications	Scopus Citations
Mottram, S., Woledge, R.C., Morrissey, D. **2009.** Motion analysis study of a scapular orientation exercise and subjects' ability to learn the exercise. *Man.Ther*. 14, 13-18.	Conceptualisation of research project. Research design, methodology, data collection and analysis. Writing – original draft 95%, Writing – review & editing.	48
Mottram, S. Dynamic stability of the scapula. **1997**. *Man Ther*. 2, 123-131.	Sole author.	162
Mottram, S., Comerford, M. **2008**. A new perspective on risk assessment. *Phys Ther Sport*, 9, 40-51.	Conceptualisation of masterclass. Writing – original draft 50%, Writing – review & editing.	45
Nijs, J.; Roussel, N., Struyf, F., **Mottram, S**., Meeusen, R. **2007.** Clinical assessment of scapular positioning in patients with shoulder pain: state of the art. *J.Manipulative Physiol Ther.* 30, 69-75.	Knowledge in movement issues around scapular, supporting science, assessment and retraining. Writing – review & editing.	41
Rowsome, K., Comerford, M., **Mottram, S.**, Samuel, D., Stokes, M. **2016.** Movement control testing of older people in community settings: description of a screening tool and intra-rater reliability. *Working Papers in the Health Sciences*, 1, 1-12.	Clinical lead, knowledge in application of tests. Writing – review & editing.	-

Publication	Original contribution by S Mottram to publications	Scopus Citations
Roussel, N., Nijs, J., **Mottram, S**., Van, M.A., Truijen, S., Stassijns, G. **2009**. Altered lumbopelvic movement control but not generalized joint hypermobility is associated with increased injury in dancers. A prospective study. *Man.Ther.* 14(6):630-5.	Concept of movement impairment assessment strategies. Writing – review & editing.	83
Roussel, N., De Kooning, M., Schütt, A., **Mottram, S**., Truijen, S., Nijs, J., Daenen, L. **2013.** Motor control and low back pain in dancers. *Int J Sports Med,* 34, 138-143.	Concept of movement impairment assessment strategies. Writing – review & editing.	27
Roussel, N., Nijs, J., Truijen, S., Vervecken, L., **Mottram, S**., Stassijns, G. **2009**. Altered breathing patterns during lumbopelvic motor control tests in chronic low back pain: a case-control study *Eur Spine J*, 18, 1066-1073.	Concept of movement impairment assessment strategies. Writing – review & editing.	32
Struyf, F., Nijs, J.; **Mottram, S**., Roussel, N., Cools, A., Meeusen, R. **2014**. Clinical assessment of the scapula: a review of the literature. *Br J Sports Med*, 48, 883-890.	Concept of movement impairment assessment strategies. Writing – review & editing.	39
Struyf, F., Nijs, J.; Mollekens, S., Jeurissen, I., Truijen, S., **Mottram, S**., Meeusen, R. **2013**. Scapular-focused treatment in patients with shoulder impingement syndrome: a randomized clinical trial. *Clin Rheumatol*, 32, 73-85.	Concept of movement impairment assessment strategies. Writing – review & editing.	79

Publication	Original contribution by S Mottram to publications	Scopus Citations
Struyf, F., Nijs, J., Meeus, M., Roussel, N.A., **Mottram, S**., Truijen, S., Meeusen, R. **2014.** Does scapular positioning predict shoulder pain in recreational overhead athletes? *Int J Sports Med*, 35, 75-82.	Concept of movement impairment assessment strategies. Writing – review & editing.	37
Struyf, F., Nijs, J., Horsten, S., **Mottram, S**., Truijen, S., Meeusen, R. **2011.** Scapular positioning and motor control in children and adults: a laboratory study using clinical measures. *Man Ther*, 16, 155-160.	Concept of movement impairment assessment strategies. Writing – review & editing.	14
Struyf, F., Nijs, J., De Graeve, J., **Mottram, S**., Meeusen, R. **2011.** Scapular positioning in overhead athletes with and without shoulder pain: a case-control study. *Scand J Med Sci Sports*, 21.	Concept of movement impairment assessment strategies. Writing – review & editing.	17
Struyf, F., Nijs, J.; De Coninck, K., Giunta, M.; **Mottram, S**., Meeusen, R. **2009.** Clinical assessment of scapular positioning in musicians: an intertester reliability study. *J Athl Train*, 44.	Concept of movement impairment assessment strategies. Writing – review & editing.	41
Struyf, F., Nijs, J., Baeyens, J.P., **Mottram, S**., Meeusen, R. **2011.** Scapular positioning and movement in unimpaired shoulders, shoulder impingement syndrome, and glenohumeral instability. *Scand J Med Sci Sports*, 21.	Concept of movement impairment assessment strategies. Writing – review & editing.	101

Publication	Original contribution by S Mottram to publications	Scopus Citations
Warner, M.B., Whatling, G.; Worsley, P.R., **Mottram, S**., Chappell, P.H.; Holt, C.A.; Stokes, M.J. **2015.** Objective classification of scapular kinematics in participants with movement faults of the scapula on clinical assessment. *Comput Methods Biomech Biomed Engin*, *18*, 782-789.	Concept of movement impairment assessment strategies. Collection of original data set. Writing – review & editing.	4
Warner, M., Wilson, D., Heller, M.O., Wood, D., Worsley, P., **Mottram, S**., Webborn, N., Veeger, D., Batt, M. **2018.** Scapular kinematics in professional wheelchair tennis players. *Clin Biomech (Bristol, Avon)*, *53*, 7-13.	Concept of movement impairment assessment strategies. Writing – review & editing.	2
Webb, N., Rowsome, K., Ewings, S., Comerford, M., Stokes, M.; **S, Mottram**. **2018.** A 'Movement Screening Test' of Functional Control Ability in Female Recreation Golfers and Non-Golfers over the Age of 80 Years: A Reliability Study. *J. Funct. Morphol. Kinesiol.*, 3. *3*(4), 54	Clinical lead, knowledge in application of tests. Writing – review & editing.	1
Worsley, P., Warner, M., **Mottram, S**.; Gadola, S., Veeger, H.E., Hermens, H., Morrissey, D., Little, P., Cooper, C., Carr, A., et al. **2013.** Motor control retraining exercises for shoulder impingement: effects on function, muscle activation, and biomechanics in young adults. *J Shoulder Elbow Surg*, *22*, e11-19.	Clinical lead, knowledge in application of tests. Design of methodology, interpretation of results. Writing – review & editing.	77

Appendix B Publications Related to Development of Theoretical Concepts

Publications, by the author, relating theoretical concepts of assessment and retraining of Movement Coordination Strategies; 1997 – 2020, and key words.

Dynamic stability of the scapula (Mottram, 1997)
Described ‘**scapular setting’**, as dynamic **orientation** of the scapula in a position to optimise the position of the glenoid so to allow mobility and stability of the glenohumeral joint. Guidelines for the clinical observation of scapular orientation with the arm by side, were presented. A rehabilitation programme was presented including: o changing the orientation with arm by side with facilitation strategies with progression to controlling orientation with arm movement o controlling orientation with arm overhead and with movements.
Review: Movement and stability dysfunction-contemporary developments (Comerford and Mottram, 2001b) **Masterclass: Functional stability re-training: principles and strategies for managing mechanical dysfunction** (Comerford and Mottram, 2001a)
Review: presented a model of **movement dysfunction** and a narrative of literature to support the model, particularly relevant to management of musculoskeletal disorders. Development of this concept was influenced by Sahrmann, who advocated using a movement system diagnoses in physiotherapy and movement examination for assessing patient’s preferred alignment and movements, rather than ‘treatment systems’ that do not address underlying problems (Sahrmann, 2002). The masterclass presented the concept of functional **stability** being dependant on the integrated function of the local and global muscle systems. **Stability dysfunction** was characterised by **site and direction** of **give o**r **compensation** and identified at a segmental and multi-segmental level. **Principles of retraining**

movement dysfunction were detailed in eight steps from controlling the **neutral alignment** to sport specific skills, targeting retraining of the local and global muscle systems.
A new perspective on risk assessment (Mottram and Comerford, 2008)
Novel assessment process of identifying **uncontrolled movement (UCM)/weak link** (formally give), from multiple muscle interactions acting on multiple joints in functionally orientated tasks, with movement tests. Uncontrolled movement characterised of by **site, direction and threshold ®**. Testing targeted both **low and high threshold recruitment**. The concept for **The Performance Matrix** was outlined, and how this can be used to assess for weak links not only in those with pain and a history of pain but also pain free individuals and considered in relation to **performance issues and risk of injury**. Differences between retraining **low and high threshold recruitment weak links** were described.
Kinetic Control, The Management of Uncontrolled Movement (Comerford and Mottram, 2012)
This textbook described the management of **movement dysfunction** through the assessment and retraining of **uncontrolled movement (UCM).** A **clinical reasoning framework** was presented to help clinicians' reason through the assessment and retraining of UCM. Eighty-four **cognitive movement control tests** were described for the low back and pelvis, hip, neck, shoulder and thoracic spine. Distinctive descriptive elements were set out for each test; start position, test movement, end position and the benchmark standard. A movement control rating system to score the test was detailed and UMC were characterised by **site, direction and threshold®**. Shirley Sahrmann wrote the foreword and described the book as having 'particular value in the comprehensiveness and detailed descriptions of possible tissue dysfunctions as reported in the literature, methods of analysis and treatment'.

The assessment of movement health in clinical practice: A multidimensional perspective (Dingenen et al., 2018)
This paper broadens the motor control concept (through dynamic system theory, see section 2.1) to include the integration of cognitive, behavioural, emotional, lifestyle, social, cultural and contextual factors on movement outcomes. Key terms discussed; **movement coordination strategies (MCS), movement health**, evaluation of preferred movement patterns, cognitive movement control evaluation, movement evaluation model.
Assessment of movement coordination strategies to inform health of movement and guide retraining interventions (Mottram and Blandford, 2020)
Introduces the concept set out in this thesis; the health of movement may be informed by the ability to display choices in **movement coordination strategies (MCS)**. This paper sets out assessment of MCS, with **cognitive movement control tests** and an **observational rating of MCS**. An inability to display choice in MCS is described as **loss of movement choices (LMC). Cognitive movement control retraining** is proposed to restore LMC. The **neutral training region** is described.

Appendix C Milestones Investigating Loss of Movement Choices at the Scapula and Retraining

Research projects and theoretical concepts, involving author of this thesis, developing the concept of assessing for loss of movement choices at the scapula and effect of movement retraining.

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1. **1997 Masterclass: Dynamic stability of the scapula** (Mottram, 1997)

Theoretical concepts: Based on clinical observation, individuals with neck or shoulder pain often present with the scapula resting in a position of more downward rotation and anterior tilt. Assessment and retraining strategies to evaluate the 'dynamic stability of the scapula' are outlined.

Relevance: These clinical observations and clinical assessment and retraining strategies were the basis for subsequent research.

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2. **2006 Pilot data** (unpublished)

Two individuals one with a history of shoulder pain and one without. Kinematic data of scapular movements captured during the cognitive movement control test (CMCT), Arm Flexion Test.

Results: Scapular movements could be measured in terms of degrees of rotation and translation. The individual with a history of shoulder pain demonstrated loss movement choices, site, (scapula), direction, (downward rotation).

Relevance: These case studies contributed to the grant proposal set out below to explore the kinematics of during the CMCT Arm Flexion Test.

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3. **2007 Award of grant from the Private Physiotherapy Education Fund** (PPEF) for project *Objective Measurements of Clinical Tests of Dissociation of the Scapula using Motion Analysis*

Methods: 13 individuals, with no history of shoulder pain and 6 with a history of shoulder pain.

Study 1. Shoulder kinematics measured on performance of the Arm Flexion cognitive movement control test (Mottram et al., 2009a).

Results: At 90° flexion significantly greater upward rotation *(p=0.03*) occurred in control group (-13.2° ± 4.6) compared with the pain history group (-7.8° ± 5.3). A greater difference (8.2°, *p=0.004*) occurred between the groups at the end of the test: (-0.3 ° ± 4.4) controls; and (7.9° ± 6.4) in the history of pain group, indicating greater downward rotation of the scapula at the end of the test.

Relevance*:* These results demonstrate changes in scapular kinematics during a cognitive movement control test of the scapula in people with shoulder pain.

Study 2. Resting and therapist-corrected orientation of the scapula (Mottram et al., 2011a)

Results: The history of pain group showed a significant increase (p<0.025) in upward rotation from the resting (-8.6° ± 8.6) to the 'neutral' position (-5.1° ± 8.0). No significant differences found in two other scapular rotations or control group.

Relevance: the history of pain group required greater scapular repositioning than the control group to achieve a position, confirms clinical observations that people with shoulder dysfunction may have altered scapular orientation.

4. 2009 Motion analysis study of a scapular orientation exercise and subjects' ability to learn the exercise (Mottram et al., 2009b)

Methods: 13 healthy participants were taught a scapular orientation exercise; kinematic measurement of scapula position and surface electromyography measured muscle activity.

Results: The scapula moved into upward rotation (mean = 4°, EM = 0.9°) and posterior rotation (mean = 4°, EM = 1.6°). All parts of the trapezius muscle demonstrated significant activity in maintaining this position, latissimus dorsi did not.

Relevance: Results demonstrate a therapist can teach movements of the scapula into upward rotation and posterior tilt and individuals can reproduce this position. Trapezius were active but because of technical difficulties (electrode placement) serratus anterior was not measured.

5. 2010 Altered scapular orientation during arm elevation (Helgadottir et al., 2010)

Methods: Insidious onset neck pain (IONP) n=21, whiplash associated disorders (WAD) n = 23 and control n = 20 (all right-handed). Scapula kinematics measured during arm elevation.

Results: WAD demonstrated increased scapula elevation compared to controls and IONP ($P<.05$), differences between posterior tilt on left side between WAD and IONP ($p<.05$).

Relevance: Altered scapular orientation is noted, on arm elevation, in individuals with neck pain and may be different between IONP and WAD. A high level of variability observed was in individuals and differences between IONP group and WAD was noted so findings cannot be generalised to all people with neck pain. The suggests need to explore the mechanisms of the altered scapular orientation on elevation including the function of scapula muscle including serratus anterior.

6. **2010** Award of grant from Solent Healthcare (UK) for a post-doctoral researcher in project *Proof of concept study of an exercise-based therapy intervention for treating shoulder pain and movement dysfunction.* The results from PPEF pump-priming project grant were used in application.

7. **2011 Single case study** (Mottram et al., 2011b)

***Aim*:** to provide proof-of-concept for a motor control retraining exercise intervention for managing loss of movement choices (LMC) at the scapula.

Methods: Male (age 51) with a history (>20 years) of recurrent right shoulder pain; currently pain free active shoulder range of motion to 135 degrees of elevation. Kinematic data of scapular measured on cognitive movement control test (CMCT) Arm Flexion before and after a 10-week movement retraining to control scapular orientation.

Results: Upward scapular rotation was increased during the CMCT (i.e., LMC into downward rotation reduced). The Increase in upward rotation placed the participant within 1 SD from the mean of healthy control data (compared to PPEF data above). The individual reported improved functional abilities after many years of restriction, such as reaching to high shelves in the garage, being able to lift heavy objects and to lie on affected side in bed.

Relevance: A 10-week movement retraining to control scapular orientation demonstrates change scapula kinematics in MCS and improvement of LMC (site, scapula; direction, downward rotation on CMCT).

8. 2011 Altered alignment of the shoulder girdle and cervical spine in patients with neck pain (Helgadottir et al., 2011)

Methods: Insidious onset neck pain (IONP) n=21, whiplash associated disorders (WAD) n = 23 and control n = 20 (all right-handed). Scapula kinematics measured at rest with arm by the side.

Results: on left side i) reduced clavicle elevation was observed in with IONP (p= 0.2) ii) reduced upward rotation in WAD (p< 03) compared to control group.

Relevance: reduced clavicular elevation, noted by a dropped shoulder is noted clinically in people with neck pain (Mottram, 1997). This change in alignment may be associated with loss movement choices, for site (scapula) and direction (downward rotation) and can be tested for with the Arm Flexion test. This may be associated with changes in muscle synergy recruitment of serratus anterior and lower trapezius, which contribute to controlling the orientation of the scapula.

9. 2013 Motor Control Retraining Exercises for Shoulder Impingement (Worsley et al., 2013)

Methods: 16 individuals with Shoulder Impingement Syndrome (SIS), 16 healthy participants. Motion analysis and electromyography recorded scapular kinematics and muscle activity during arm elevation to 90°. Individuals with SIS underwent a scapular orientation retraining.

Results: Post intervention the SIS group demonstrates a significantly reduced score on Shoulder Pain and Disability Index ($p > 0.001$), a mean reduction of 10-point Visual Analogue Scale of pain of 3.4 points, upward rotation and posterior tilt of the scapula increased significantly ($p > 0.05$).

Premature termination of lower trapezius (LT) ($p<0.05$) and serratus anterior (SA) ($p>0.05$) activity were shown pre-intervention during the arm lowering phase of the test, at an arm angle of 27° ± 15 and 28° ± 15 compared to healthy individuals (mean arm angle 17° ± 8 and 22° ± 10). Duration of activity in LT and SA muscles was increased significantly ($p<0.05$) post-intervention, with muscle activity terminating at an arm angle of 19° ± 7 and 17° ± 8 respectively, to match that of the healthy participants.

Relevance: A 10-week motor control intervention, including scapular orientation retraining, increased function and changed pain in individuals with SIS. The recovery mechanisms involved improvements in in muscle recruitment patterns including SA and scapular kinematics.

Scapula kinematic measures during Arm Flexion cognitive movement control test (CMCT) (in preparation).

From the same data set: Seven out of the 19 participants (37%) failed the Arm Flexion CMCT and had a significantly lower downward rotation of the scapular between the start and end of the test (-7°, SD±2.4; p<0.001; Fig 3). There was no significant difference (p=0.135) in downward rotation (-1°, SD±2.1) in participants who passed the SFSMC test. (Mottram in preparation) (Mottram et al., 2012b).

10. 2013 Scapular-focused treatment in patients with shoulder impingement syndrome: a randomized clinical trial (Struyf et al., 2013).

Methods:Randomised control trial, 22 patients with Shoulder Impingement Syndrome (SIS); scapula focus group, movement retraining and orientation (10) versus eccentric strength training, ultrasound and fictions (12).

Results: The scapular focused group self-reported Shoulder Disability Questionnaire illustrated a large clinically important effect (Cohen's d=0.93, p=0.025), and maintained at three months follow up. The scapula focused group demonstrated a moderate (Cohen's d=0.67) improvement in self-reported pain at rest, whereas control group did not.

Relevance: Scapular-focused retraining group, demonstrated reduced pain and disability in people with SIS, compared to controls (eccentric cuff exercises).

11. 2015 Objective classification of scapular kinematics in participants with movement faults of the scapula on clinical assessment (Warner et al., 2015)

Aim**:** to use a multivariant classification tool to objectively classify participants who failed cognitive movement control tests (CMCTs), using data from PPEF study.

Methods: Principal component scores and discrete kinematic variables (scapula kinematics on the CMCT) were used as input into classifier.

Results: Five out of six participants with a history of shoulder pain classified as having loss of movement choices (LMC), with an accuracy of 72%. Variables related to upward rotation of the scapula had most influence on the classification. Three individuals, with no history of shoulder pain, were represented towards the LMC classification.

Relevance: The classification model could objectively classify individuals, who demonstrated LMC on the CMCT, based on kinematic variables, suggesting the CMCT is a useful tool to identify LMC. Changes in kinematics (MCS) were noted in three people without shoulder pain, illustrating movement faults can be present in people without a history of shoulder pain.

Appendix D Morphometry of Serratus Anterior and Proposed Actions

Attachment, mean fascicle angle, physiological cross-sectional area and proposed actions of serratus anterior (Webb et al., 2018a).

Upper division
Attachments: Rib 1 and 2 superior fascicles attach to the medial and superior borders of the scapula (superior angle). **Mean fascicle angle:** Relative to the vertical midline, **physiological cross-sectional area (PCSA)** areas: 29° and 1.3cm^2. **Proposed action:** • Controls and anchors the superior angle during scapular rotation, on arm elevation, due to the short thick rib 1 and rib 2 superior fascicles attaching to both borders of the superior angle of the scapula and orientated closer to the vertical midline (passing inferior to ribs 1 and 2). The longer tendon of the rib 2 superior, at the scapular end, could contribute to directing the forces required to anchor the superior angle. It is proposed the upper division helps maintain optimum scapular orientation and relative scapula upward rotation, by keeping the superior angle inferior to the acromion. • Controls external rotation of the scapula by anchoring the superior angle.

Middle division

Attachments: Rib 2 inferior and rib 3 fascicles pass to the medial border.

Mean fascicle angle: Relative to the vertical midline, **PCSA**: 90° and 2.2cm^2 (rib 2 inferior fascicle had the largest cross section area).

Proposed action:

- Produces external rotation (and controlling internal rotation/winging) of the scapula at the acromioclavicular joint (pulling the medial border and inferior angle of the scapula towards the chest wall) as protraction of the clavicle at the sternoclavicular joint occurs. Because of large PCSA may have a significant influence on controlling scapular winging.

Lower division

Attachments: Rib 4s to 8/9 fascicles attached at the inferior angle

Mean fascicle angle: Relative to the vertical midline, **PCSA**: 59° and 3.0cm^2

Proposed action:

- Pulls the inferior angle laterally around the chest wall (away from the midline) supports a primary role of upward rotation of the scapula and controls downward rotation (Worsley et al., 2013).
- Powerful protractor of the shoulder girdle (e.g. pushing). The lower digitations rotate the scapula laterally (upward rotation of the glenoid) to optimise the position of the glenoid.

Control function: resists the pull of trapezius and keeps the medial border against the chest wall with upper limb movements.

Appendix E Papers in Addition to Five Core Publications, Presenting Changes in Kinematic and Neurophysiology

Publications by author of thesis, presenting changes in kinematic and neurophysiology, across different cohorts.

Scapular kinematics in professional wheelchair tennis players (Warner et al., 2018)
Methods: Scapula kinematics recorded during arm elevation and lowering in 11 professional wheelchair tennis players, 16 non-wheelchair users with shoulder impingement syndrome (SIS) and 16 non-wheelchair users (controls) without SIS. Professional wheelchair tennis players experienced little shoulder pain (scored on Wheelchair Users Shoulder Pain Index) and clinical examination revealed negative impingement tests. ***Results:*** Wheelchair tennis players had greater scapular posterior tilt during humeral elevation (3.9°, p = 0.05) and lowering (4.3° p = 0.04) on the dominant compared to the non-dominant side. The dominant scapulae wheelchair tennis players were significantly (p=.014) more upwardly rotated (21° SD6.7) than scapulae of individuals with SIS (14.1°) during arm elevation (scapula humeral plane).
Altered breathing patterns during cognitive movement control tests (Roussel et al., 2009a)
Methods: 10 healthy individuals, 10 individuals with chronic low back pain. Breathing pattern was evaluated at rest and whilst performing CMCTs (Bent Knee Fall Out and Knee Lift Abdominal Test). ***Results:*** Breathing patterns were observed in people with chronic low-back pain whilst performing CMCTs compared to controls (p=0.01).

Appendix F Intra and Inter-rater Reliability (Experienced Raters)

Methodology and results for intra and inter-rater reliability of screening for movement impairments (experienced raters) **(Mischiati et al., 2015)**.

Methods: 20 university sports students performed nine CMCTs, from The Foundation Matrix movement screen and were scored by two experienced therapists. 75 criteria were rated pass or fail.

Results: **inter-rater reliability**

- Good inter-rater reliability: overall test percentage agreement was 78%, overall intraclass correlation coefficients (ICC) 0.81
- Individual components (for 75 criteria) percentage agreements ranged from 68-100%, Kappa ranges 0.0-1.0

intra-rater reliability

- Excellent intra-rater reliability:

  Rater 1, overall test percentage agreement was 98%, ICCs 0.96

  Rater 2, overall test percentage agreement was 94% and ICCs 0.88,
- Individual components percentage agreements ranged from 88-100% (Rater 1), and 75-100% (Rater 2), Kappa ranges 0.6-1.0 (Rater 1) and -0.1-1.0 (Rater 2)

real-time vs video

- Moderate to poor real-time vs video (overall test percentage agreement was 75%, ICCs 0.23), individual components percentage agreements ranged 31-100%, Kappa ranges -0.1-1.0.

Appendix G Elements Enhancing Cognitive Movement Retraining

Some elements of cognitive movement control retraining used by the author's movement coaching practice.

Explain movement
Explain Pain aims to give people in pain the power to challenge pain and consider new models for viewing what happens to the body and brain with pain (Butler and Moseley, 2013). Once they have learnt about the processes involved, they can follow a scientific route to recovery. A similar process can be followed to educate individuals on science behind movement coordination strategies (MCS), how these changes influence the health of their movement and what they can do to change their MCS in short and long-term.
Movement coaching
Coaching: 'I cannot teach anybody anything; I can only make them think' (Socrates); (Wilson, 2014). This illustrates a coaching philosopher's approach and differs from just giving instructions. Coaches work on improving the performance and wellbeing of individuals, by challenging and encouraging mindsets through goals setting, exploring values and beliefs, and facilitating action plans; and is achieved by enhancing awareness and self-directed learning (Wilson, 2014). This is an important consideration in movement retraining. **Knowing:** There is a fundamental difference between theory and practice. Immediately recognising patterns without hesitation is not always sufficient and observations may require mental processing. Knowing does more than rely only on conceptual and intuitive models to develop expertise. Facilitating a change in movement coordination strategies requires putting theory into practice and developing expertise. Assessment of movement coordination strategies and linking to the individual's goals can foster clarity (knowing) and confidence to make changes.

Communication is the act of expressing (or transmitting) ideas, information, imagery, knowledge, thoughts, and feelings, as well as understanding what is expressed by others (Burton and Raedeke, 2008). Movement coaching to restore loss of movement choices requires an individual to change movement patterns in the context of numerous constraints see section 2.1.1. Exercise prescription may well be a key feature of the action plan, but this table illustrates an interplay of holistic factors which therapists can draw on to improve the performance of movement coordination strategies to enhance the health of movement. Communication is at the heart of movement retraining. It involves not only the delivery of movement retraining plan but also its emotional impact and the effect on the individual.
Embodiment
Embodiment can be described as subjective awareness (from inside), through which we feel, think, perceive the world, relate and take action. It is the subjective awareness, attention, intention, posture, breathing and movement. (The Embodiment Channel, 2013) It is how we are / the way we are. This awareness of the body and as a body brings choices and individuals can discover movement options and adaptability. This can facilitate awareness to movement coordination strategies and how they relate to attention, intention, posture, breathing and movement.
Encouraging self-directed learning
The principles of self-directed learning include awareness, responsibility, self-belief, blame free, solution focused, challenge, action, and trust. Movement coaching can facilitate self -directed learning in individuals as they explore retraining loss of movement choices (Wilson, 2014).
Flow
Flow captures the positive mental state of being completely absorbed, focused and involved in activities at a certain point in time, as well as deriving enjoyment for being engaged in that activity (Csikszentmihalyi, 1990). Features of flow which support the retraining if MCS include:

- Setting goals and monitoring feedback
- Becoming immersed in the activity
- Paying attention to what is happening
- Enjoying the immediate experience.

Flow can influence restoring loss of movement choices by:

- Achieving a balance between ability and challenge by matching the retraining to the individual
- Matching retraining and awareness
- Agreeing clear movement goals to enhance the flow experience
- Receiving positive feedback is a key construct of the flow experience
- Encouraging concentration / immersion in the practice
- Facilitating intrinsic enjoyment in retraining programme and challenge as training progresses
- Creating positive and enjoyable learning environment.

Mindful movement and skilled attention

- There is a strong evidence to support a relationship between movement skill and attentional and cognitive control (Clark et al., 2015).
- Motor planning and attentional control share a dependency on the same kind of information e.g. about the environment, the body and how they relate in behaviour – sensorimotor coordination (Clark et al., 2015).
- Provides a mechanistic basis for mind-body connection, and effects of mindful movement practice.

The cognitive element of any retraining strategy can be facilitated with a focus on mindful movement with attention, intention, breath, repetition and a mind-body connection including awareness of movement. Much can be learnt from mindful movement practices e.g. Tai Chi, Garuda (see **Figure 1.3**). These principles of mindful movement were employed during the case study publication included in this thesis (**Mottram et al., 2019).** This was particularly so during the cognitive phase of motor learning where the feedback about the movement was important (taking this rehearsal into the practice and autonomous phase).
Understanding the individual's narrative
Understanding an individual's story and the experiences they describe (Douglas and Carless, 2015). May help individuals and practitioners to become self-aware, self-reflective and self-critical. An individual's story and experiences may be a factor influencing movement coordination strategies and fit within the clinical reasoning process.
Finding a Meaning for an Individual
Exploring a narrative reflects individuals' perspective of their situation. Understanding the narrative of the individual has been shown to be important in practice (Solvang and Fougner, 2016). Discovering an individual's passions and experiences can harnessed to expand movement options.
Goal setting and making a pledge
Although goal setting is regularly used in rehab settings, a Cochrane review found there is very low-quality evidence that goal setting may improve some outcomes (Levack et al., 2015). A pledge, however, does not have an endpoint and is something we are working on constantly. A pledge enables curiosity and

can enhance resilience. As the health of movement is with the individual for a lifetime, a pledge to sustain healthy movement, by restoring movement options within the confines of constraints (see 2.1) may help maintain health and quality of life across the lifespan.
Therapeutic alliance
Many of the principles mentioned in this table are attributes of the concept of therapeutic alliance outlined from a thematic analysis (Sondena et al., 2020). These attributes include: • Seeing the person: individualised care, person over pathology, equality, unique individual, world view, value and beliefs, acceptance • Sharing the journey: role change, holistic, behaviour change • Communication: attention to the narrative, verbal and non-verbal, empathy, active listening, language • Fostering autonomy: shared decision making, self-awareness, self-reflection, self-efficacy, behavioural change, self-management, responsibility. These attributes within the therapeutic alliance, may improve therapeutic outcomes and patient engagement (Miciak et al., 2018). In relation to restoring LMC, understanding the relationship between the site and direction of LMC, the short- and long-term goals, narrative and significant constraints (see 2.1), can enhance the communication between therapist and person to support practice and long-term outcomes.

Appendix H Key Elements Central to a Movement Coaching Practice.

Illustration of some practical strategies, used by the author in clinical practice, which may influence the brain and enhance motor learning and recovery of loss of movement choices.

Cognitive motor imagery
Imagery can be a powerful tool that can affect learning, improve performance and skill acquisition, improving focus and motivation. (Ritchie and Brooker, 2018, Abraham et al., 2019, Zapparoli et al., 2020, Yamada et al., 2020, Renner et al., 2019). With motor imagery movements are mentally rehearsed without overt actions and can include imagination or cognitive imitation of a task and may include visual or verbal stimuli (Zapparoli et al., 2020). Imagery maybe a valuable strategy to employ when movement coaching. Various movement methods e.g., Garuda and Pilates put a strong emphasis on this strategy and something I champion in practice. My teaching practice encourages clinicians to widen their movement vocabulary away for anatomical and biomechanical terms to a more creative/image-based language. Motor imagery has been shown to more effective over verbal cues of a motor task based on a movement control exercise and tactile cues (La Touche et al., 2020).
Attentional focus strategies
Attentional focus can be explained as: • Internal focus attention is focused on body e.g., ‘keep the knee over the toe’ • External focus – attention is directed away from the body to the outcome or effects of the movement e.g., ‘keep the bar level’.

An external focus of attention has been shown to beneficial for learning and performance (Neumann, 2019, Gokeler et al., 2019, Wulf et al., 2010). Internal focus may have value at early cognitive stage of motor learning as individual gains and awareness and understanding of loss of movement choices (LMC) and how to relearn movement choices to regain LMC. However, as motor learning progresses to the autonomous and automatic stages external focus strategies are best employed to progress the challenge of regaining choices in movement coordination strategies.

Feedback
When a learner experiences success and efficacy it is connected with motivation and a positive effect on learning; this helps learner be aware of self-improvement over time (Chiviacowsky, 2020). Cognitive movement retraining is focusing on restoring lost movement choices how feedback is experienced will influence to motor learning process. Implicit feedback encouraged by elements in Appendix G can support the motor learning process. Explicit feedback needs to be positive to encourage motivation need for the repetitive practice required to recover movement options.

Appendix I Quotes and Testimonials

Narrative from an individual improving the health of their movement for performance; John Evans
'As a former rugby player, I had suffered numerous soft tissue injuries including a significant tear to my oblique abdominals. I was experiencing frustration with my weightlifting training and despite some gains in strength was struggling with overhead lifts especially the snatch and the jerk. Despite regular focused strength training this was not reflected in improvements in the key lifts. I felt out of balance and not fully in control of the bar and small adjustments to my technical model were not paying dividends. I was doing a lot of mobility work and yoga 1 or 2 twice a week and while this was useful it did not bring the changes I needed. On meeting me Sarah quickly noted that my rib position was not quite right and moved swiftly to observe me during movement. She identified that I struggled with specific movements despite my focus on strength and mobility. Sarah was able to facilitate me to find the know how to use new movement patterns which I had previously been unable to access. In addition, I learned to avoid old compensation patterns that had become stuck and counterproductive. My lifts became better and more controlled, my recovery from them was quicker and I could apply my strength more effectively. I felt that I could trust my movement to a greater degree. Sarah's input had given me a greater kinaesthetic awareness. This was the missing link that made all the difference…..movement coaching. In addition to strength gains I was experiencing less sacroiliac joint pain which had been an historic weakness and was extremely pleased to find that my neck pain from coaching boxing pad sessions had substantially reduced. Within a small time-frame Sarah had helped me make some hugely significant changes to both my performance and resilience. She makes movement the focus and movement matters'.
An individual illustrating the influence of movement coaching on long term health; post fracture femur; young amateur athlete
'As a young athlete facing the long road to recovery following a hip fracture and subsequent operation, Sarah's guidance from an early stage and frequent touch points (face to face and virtual sessions across two years) has not only given me confidence but also the context to the understanding of my symptoms and

limitations in sport and activities, in the different phases of my recovery. Having instinctively focused on strengthening muscles, Sarah really pushed me to change my movement and focus on controlling movement and understanding my cheats and compensations. The seven touchpoints and the knowledge I have gained I can see supporting me through-out the rest of my life, a little goes a long way!'
Narrative from an elite international professional dance artist; Dr Scilla Dyke MBE
'As an elite international dance artist, advocate, academic, author and performance coach with a career spanning six decades across multiple dance genres I implicitly understand the importance of movement health across the lifespan. Sarah whom I've had the honour to engage with, over 20 years, combines a profound understanding and belief in the potential impact of movement on quality of life. The holistic integrated process within Sarah's Movement Coaching champions a strategy to embrace the individual's narrative, practice and multiplicity of styles with bespoke retraining that encompasses the breadth and depth of dance, theatre and movement. It is so much more than exercise; it is gaining insight and awareness to achieve a transformational shift in ways to move. The mind-body unity, beyond functional performance, has inspired me to utilise a bespoke palette of options to restore choices of healthy movement and acquiesce opportunities. Using the body and mind allows physical, mental and social wellbeing and gives possibilities to {re} engage with life. A meaningful and challenging holistic collaborative approach to enhance the lives of clients by restoring individual choice, for long-term health'.
The learning journey, practitioner championing the health of movement; Jacqueline Swart
'I began my 'movement journey' in 2003. Inspired by Sarah's ambition and passion for placing movement at the center of physiotherapy practice, I completed 15 of her courses. These courses enabled me to develop skills in the assessment and retraining of movement. Sarah's depth of knowledge and analytical analysis facilitated me to develop an integrated clinical reasoning framework to improve and maintain my patient's health of movement and to achieve better outcomes with symptom relief, improving function and quality of life as well as preventing recurrence. Sarah mentored me to develop my clinical reasoning and most importantly to link movement coordination strategies to clinical presentations and individual goals. I began to see how even small changes in the movement system

can have a positive impact through a person's life-course. Changing quality of life through the art of retraining movement. Sarah encouraged me to develop my own Movement Centre in South Africa, where my clinical practice changed from a manual therapy background to a health of movement focus. I am grateful to have been empowered to develop these movement skills and to integrate both practical and academic knowledge. It has been an inspirational journey for me, and I have loved being part of Sarah's own development and seeing a deeper understanding of the health of movement evolve'.
Educator in Movement; From an educator in movement; Lincoln Blandford
'As a vastly skilled, experienced, and innovative educator in movement, Sarah combines a profound understanding and belief in the potential of movement's impact on quality of life with the abilities of a world-class practitioner. When watching Sarah work with a client, there is much to admire in her expertise of observing subtleties in movement, connecting how these relate to the client's specific altered function or performance, and then teaching retraining interventions to address for the long-term'.
Application to elite sport; First Team Physiotherapist, Premiership Football
'The Football Matrix (part of The Performance Matrix), is an excellent tool for identifying the loss of movement choices an athlete demonstrates under low and high threshold situations. Using this, in conjunction with clinical reasoning, helps support a comprehensive rehabilitation plan, targeting the conditioning of muscle synergies to diversify the movement choices specific to that athlete'.
Application to a business model; Business Owner Paul Goss, Body Logic Health
'The challenge for the modern practitioner is developing a clear clinical pathway that educates the client and helps them understand the importance of movement health. Through our integration of the Kinetic Control (KC) clinical reasoning framework to all our clinicians along with The Performance Matrix (TPM) assessment and retraining protocols clients can be educated about the importance of completing their treatment pathway. The ability to manage our client pathway has

allowed us to develop a business model based on the latest movement science to clearly take our clients to the next level. The ability to put movement at the heart of our business model through KC and TPM gives us a cutting edge USP in the current marketplace, allowing our business to thrive.'
Taking the health of movement to international territories; CMS Tutor Suzanne Tang
'I took my first Kinetic Control, in Taiwan in 2014. I immediately saw the clinical application of the movement tests and retraining and also the logical clinical framework and the strong evidence base. This clinical reasoning offers the 'why' and 'how' and integrates existing skills sets and allows the clinician to improve efficiency in clinical practice and drive patient-focused care. This empowers physiotherapists to collaborate with other professions with confidence. *Guided by Sarah the CMS accredited tutor training programme has enabled me to share my knowledge with practitioners. I have been teaching for 3 years, have taught 130 days, to about 650-700 clinicians, in Taiwan, Macau, Hong Kong and Mainland China. The enthusiasm of students and their eagerness to put this work into practice has been transformative. Sarah has coached my journey by helping me optimise my clinical skills, facilitate the clinical reasoning process and deliver knowledge efficiently and engagingly. She encouraged me to set up a now successful teaching business. Sarah has also guided me to recruit and train other tutors so that we can share the knowledge to more therapists'.*

Core Publications

Summary sheet of five core publications.

1. Dingenen, B., Blandford, L., Comerford, M., Staes, F. & **Mottram, S**. 2018. The assessment of movement health in clinical practice: A multidimensional perspective. Phys Ther Sport, 32, 282-292.

2. **Mottram, S**. & Blandford, L. 2020. Assessment of movement coordination strategies to inform health of movement and guide retraining interventions. Musculoskelet Sci Pract, 45, 102100.

3. **Mottram, S**., Warner, M., Booysen, N., Bahain-Steenman, K. & Stokes, M. 2019. Retraining in a female elite rower with persistent symptoms post-arthroscopy for femoroacetabular impingement syndrome: a proof-of-concept case report. J. Funct. Morphol. Kinesiol, 4(2), 24.

4. Webb, A. L., O'Sullivan, E., Stokes, M. & **Mottram, S**. 2018. A novel cadaveric study of the morphometry of the serratus anterior muscle: one part, two parts, three parts, four? Anat Sci Int, 93, 98-107.

5. Mischiati, C., Comerford, M., Gosford, E., Swart, J., Ewings, S., Botha, N., Stokes, M. & **Mottram, S**. 2015. Intra and inter-rater reliability of screening for movement impairments: movement control tests from the foundation matrix. J Sports Sci Med, 14, 427-40.

Core Publication 1: Dingenen et al., 2018

Dingenen, B., Blandford, L., Comerford, M., Staes, F. & **Mottram, S**. 2018. The assessment of movement health in clinical practice: A multidimensional perspective. Phys Ther Sport, 32, 282-292.

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Masterclass

The assessment of movement health in clinical practice: A multidimensional perspective

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ABSTRACT

This masterclass takes a multidimensional approach to movement assessment in clinical practice. It seeks to provide innovative views on both emerging and more established methods of assessing movement within the world of movement health, injury prevention and rehabilitation. A historical perspective of the value and complexity of human movement, the role of a physical therapist in function of movement health evaluation across the entire lifespan and a critical appraisal of the current evidence-based approach to identify individual relevant movement patterns is presented. To assist a physical therapist in their role as a movement system specialist, a clinical-oriented overview of current movement-based approaches is proposed within this multidimensional perspective to facilitate the translation of science into practice and vice versa. A Movement Evaluation Model is presented and focuses on the measurable movement outcome of resultants on numerous interactions of individual, environmental and task constraints. The model blends the analysis of preferred movement strategies with a battery of cognitive movement control tests to assist clinical judgement as to how to optimize movement health across an individual lifespan.

1. Introduction: the value of movement

Movement is everywhere in human life and is rated as critical to a person's ability to participate in society (American Physical Therapy Association, 2013). "Movement is life", as stated by the "father" of Western medicine, Hippocrates, neatly captures what movement allows, a statement succinctly revealing movement's necessity. Movement offers a means of interaction with the world, facilitating each action, from the artist's brushstroke to the sprinter's world record. The importance of movement in the maintenance of both health and quality of life has been highlighted (Bauman, Merom, Bull, Buchner, & Fiatarone Singh, 2016; Haskell et al., 2007; Rhodes, Janssen, Bredin, Warburton, & Bauman, 2017), hereby further elevating movement's value. An absence or decrease of human movement, manifesting as physical inactivity, is currently identified as the fourth leading risk factor for mortality, globally (World Health Organization, 2010).

Any exploration of the value of movement will typically encounter both its richness and complexity. The dynamic systems theory is respectful of such complexity as it considers how any observed movement pattern is an overt result of innumerable and often latent contributing and interactive components (Davids, Glazier, Araujo, & Bartlett, 2003; Holt, Wagenaar, & Saltzman, 2010; Newell, 1986; Wikstrom, Hubbard-Turner, & McKeon, 2013). For each individual, the multifactorial influences on movement can be summarized by the complex interaction of factors related to the individual itself (organismic constraints), the task being performed (task constraints), and the environment or context in which it is performed (environmental constraints) (Fig. 1) (Davids et al., 2003; Holt et al., 2010; Newell, 1986; Wikstrom et al., 2013). Some examples of the multiple interactive factors influencing the individual (Bates, Myer, & Hewett, 2015; Clermont, Osis, Phinyomark, & Ferber, 2017; Gokeler et al., 2013; Grooms, Appelbaum, & Onate, 2015; Herman & Barth, 2016; Hodges &

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Smeets, 2015; Janssens et al., 2014; Lima et al., 2017; Phinyomark, Hettinga, Osis, & Ferber, 2014; Savage, Lay, Wills, Lloyd, & Doyle, 2017; Sigward, Pollard, & Powers, 2012; Skalshoi et al., 2015; Taylor et al., 2017; de Souza et al., 2015), task (Schreurs, Benjaminse, & Lemmink, 2017; Vanrenterghem, Venables, Pataky, & Robinson, 2012; Willy & Davis, 2011) and environment (Albertsen, Ghedira, Gracies, & Hutin, 2017; Brown, Brughelli, & Hume, 2014; Christensen, Wilson, Merryweather, & Foreman, 2017; Dingenen et al., 2013, 2017a; Ip et al., 2017; Lo et al., 2017; Mason-Mackay, Whatman, & Reid, 2016; Schutte et al., 2016; Soares et al., 2017) are listed in Table 1. In ideal circumstances, the human movement system has the ability to spontaneously reorganize movement coordinative strategies in a variety of ways to adapt to the constantly changing task and environmental constraints (functional variability) (Davids et al., 2003; Wikstrom et al., 2013).

The reorganization of movement coordinative strategies can be viewed in the short and long term. Short-term changes in movement coordinative strategies may occur, for example, due to the presence of fatigue (Santamaria & Webster, 2010). For example, a 60 min running protocol, simulating an Australian football game, induced significantly increased knee flexion angles at initial contact and increased internal knee extension moments during sidestepping compared to pre-fatigue states (Savage et al., 2017). In the long term, previous injury has been associated with differences in biomechanical measures. For example, in a systematic review, Gokeler et al. (Gokeler et al., 2013) found that gait was altered in the sagittal, frontal and transversal planes years after anterior cruciate ligament reconstruction. In addition, an increased risk to develop tibiofemoral and patellofemoral joint osteoarthritis has been reported (Culvenor, Cook, Collins, & Crossley, 2013), which can affect knee symptoms, function and quality of life 10–20 years after anterior cruciate ligament reconstruction (Oiestad, Holm, Engebretsen, & Risberg, 2011; Risberg et al., 2016). Changes in movement coordinative strategies may persist, subsequently interfering with the ability to participate in sports activities later in life (Gribble et al., 2016; Myer et al., 2014, 2015; Rathleff, Rathleff, Olesen, Rasmussen, & Roos, 2016). A drastic decrease in physical activity as a result from an acute injury or chronic pain may predispose a person to fall into a negative continuum of physical and psychological disability (Myer et al., 2014; Stubbs et al., 2013). Therefore, the value of movement for an individual is not limited to a specific point in time, but should be considered across the continuum of an entire lifespan. For example, it is now recognized that childhood offers a unique opportunity to facilitate the development of fundamental movement skills and neuromusculoskeletal movement health, which are essential to prepare youth for a lifetime of health-enhancing physical activity (Myer et al., 2015). Unfortunately, the technology-driven environments and sedentary lifestyles which children are currently confronted with in Western society, may lead to decreased motor skill potential later in life (Myer et al., 2015), alongside many other negative consequences of physical inactivity. The value of movement and the factors seen to influence movement coordination strategies are also being recognized by the older population in a desire to support both participation and maintain health (Bauman et al., 2016; Rhodes et al., 2017). This consideration across the entirety of a person's life introduces the concept of a movement lifespan. Exploration of the multiple factors influencing movement across this broad epoch demonstrates the importance of considering the influence of the three levels of constraints on short- and long-term changes in movement coordination strategies across each individual's lifespan.

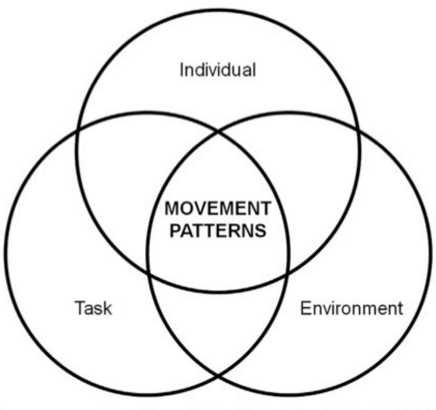

Fig. 1. Human movement is influenced by an interaction of the task, individual and environment (dynamic system theory) (adapted from Holt et al. (2010)).

The recognition of movement's value to participation and wider health highlights the need to investigate the means of maintaining the health of movement itself. Movement health has been defined as a "state in which individuals are not only injury free, but possess choice in their movement outcomes" (McNeill & Blandford, 2015). This "choice" in movement encompasses not only what movement is performed, as individuals interact and engage with their world, but also how it is performed, as they employ differing movement strategies to achieve their desired goals in both the short and long term. Movement health is something we should enjoy throughout our life, an element extending across the human lifespan, positively contributing to each individual's quality of life. In light of this perceived value, therapists should try to preserve or restore the characteristics contributing to the health of movement. However, movement coordination strategies and resulting movement patterns are influenced by multiple dynamic and interactive factors. The clinical intervention picture may be complex and must take into account a large number of relevant constraints. Even though equally important, this paper does not focus upon individual constraints such as pain, strength, mobility or fatigue, but considers means of evaluating movement, presented here as the overt outcome of multiple and complex interactions between individual, task and environmental constraints. Finally, we will propose a novel movement evaluation model within a multidimensional clinical perspective.

2. From pathokinesiology to kinesiopathology

Certain characteristics of movement may alter in the presence of injury and pain (Hodges & Smeets, 2015). This study of "abnormal" movement resulting from pathology is typically referred to as the pathokinesiological model (Sahrmann, 2002, 2011). Within this model, the diagnostic process is mainly based on the identification of the patho-anatomic structure generating pain or pathology (e.g. M. supraspinatus tendinopathy or a herniated disc). From a historical point of view, this is a longstanding approach, and is currently still prevalent. However, several limitations have been acknowledged when exclusively employing this model (Ludewig, Lawrence, & Braman, 2013). A patho-anatomic diagnostic label such as "rotator cuff disease" or "patellofemoral pain syndrome" is often very broad, ambiguous and non-specific. Different individuals with the same patho-anatomic diagnostic label may possess non-comparable, and highly discrete variations within their clinical presentations, while the same clinical presentation can be generated by a variety of other patho-anatomic structures. Diagnostic labels based on tissue-specific pathology often fail to accurately direct clinical decision-making (Cools & Michener, 2017).

Table 1
Examples of factors potentially influencing the individual, task and environment in relation to human movement health.

Individual	Gender (Phinyomark et al., 2014; Sigward et al., 2012) Age, maturation (Phinyomark et al., 2014; Sigward et al., 2012) Activity/sport level (Clermont et al., 2017) Anthropometrics (Bates et al., 2015) Anatomical, morphological (Skalshoi et al., 2015) Injury history (Gokeler et al., 2013) Movement history (e.g. previous experiences, practice, training, sport) (Taylor et al., 2017) Pain (Hodges & Smeets, 2015) Mobility, flexibility (Lima et al., 2017) Sensorimotor factors (e.g. acquisition of sensory information, neural transmission, central nervous system processing, integration and plasticity, muscle activity, muscle activation timing, inter- and intramuscular coordination, muscle strength) (Grooms et al., 2015) Fatigue (Savage et al., 2017) Psychological (e.g. beliefs, emotions, expectations, fear of movement, anxiety, motivation) (de Souza et al., 2015) Visual-perceptual skills (Grooms et al., 2015) Neurocognitive factors (e.g. reaction time, processing speed, pattern recognition, decision making) (Herman & Barth, 2016) Systemic or other physiological systems (e.g. cardiovascular, respiratory) (Janssens et al., 2014)
Task	Activity performed (e.g. running, walking, jumping, swimming, throwing, sitting) (Willy & Davis, 2011) Task constraint (e.g. direction of movement, time restraints, sports rules) (Schreurs et al., 2017; Vanrenterghem et al., 2012)
Environment	Base of support (Albertsen et al., 2017; Dingenen et al., 2013) Surface (Schutte et al., 2016) Obstacles (Christensen et al., 2017) Footwear (Soares et al., 2017) Protective equipment (e.g. bracing, taping) (Dingenen et al., 2017a; Mason-Mackay et al., 2016) School, work, society (Ip et al., 2017) Public facilities (e.g. transport, sport facilities) (Ip et al., 2017; Lo et al., 2017) Significant others (e.g. parents, friends, trainers, team mates, opponents, colleagues) (Brown et al., 2014)

Therefore, a patho-anatomical diagnosis may not always be helpful or perhaps even misdirect physical therapists' clinical judgement and cause them to deliver inadequate or ineffective interventions. The underlying phenomena eliciting the pain or injury are not specifically identified. The patho-anatomical diagnosis has led to the prevalence of using "protocols" to treat the same patho-anatomical diagnostic label, resulting in everyone with the same label getting the same treatment intervention regardless of the variations within their clinical presentations. Furthermore, increasing evidence fails to show strong relationships between structural abnormalities and function (Brinjikji et al., 2015; Teunis, Lubberts, Reilly, & Ring, 2014; Tornbjerg et al., 2017), while often the specific anatomical structure causing the pain remains unknown (Ludewig et al., 2013). These findings support the notion to evaluate a person within a multidimensional clinical reasoning approach (O'Sullivan, Caneiro, O'Keeffe, & O'Sullivan, 2016). Within a multidimensional perspective, the previously proposed dynamic system theory offers routes of explanation as to how the same interactions with a task and environment can lead to highly divergent outcomes for a specific individual, which may or may not be related to pathology, pain, symptoms and function (Davids et al., 2003; Holt et al., 2010; Newell, 1986; Wikstrom et al., 2013).

Despite the global recognition that movement in the form of physical activity and exercise can have positive consequences on general health, there is still only a limited general notion that the characteristics or "ways" a person moves impacts neuromusculoskeletal injury risk, performance and quality of life. The study of movement essential to enhance task-specific performance and prevent movement-related disorders is referred to as kinesiopathology (Sahrmann, 2014). The human movement system has a tremendous ability to adapt quickly to tissue loading to maintain tissue homeostasis and function (Dye, 2005; Hodges & Smeets, 2015; Khan & Scott, 2009). Within the concept of kinesiopathology, the loss of tissue homeostasis of innervated neuromusculoskeletal tissues is considered to be more important than the structural abnormalities of the tissues itself (Dye, 1996, 2005). The basic principle is that repeated and/or biomechanically less advantageous movements can lead to stresses to neuromusculoskeletal structures that exceed an individual's tissue capacity, which can contribute to pain, symptoms and pathology, regardless of whether the altered movement patterns may be the cause or result (Dye, 1996, 2005; Sahrmann, 2002). For example, an increased internal rotation of the femur has been related to increased patellofemoral joint stress during a squatting task in persons with patellofemoral pain (Liao, Yang, Ho, Farrokhi, & Powers, 2015). The boundaries of an individual's tissue capacity and pain tolerance are influenced by numerous factors including the sensitization of the nervous system, pain mechanisms, psychosocial factors, loading and injury history, diet and nutrition, sleep, endocrine and hormonal status, medication, diseases and systemic factors (Goom, Malliaras, Reiman, & Purdam, 2016; Warden, Davis, & Fredericson, 2014). The kinesiopathological approach was originally described by Sahrmann (Sahrmann, 2002) and leads to a redirection of a clinical examination to the identification of the movement characteristics that contribute to the development of pathological processes, instead of only focusing on the structural variations in pathological conditions (Sahrmann, 2014). Diagnostic "labels" of movement characteristics are rather focused on the underlying phenomena that assist in guiding physical therapy intervention, instead of the diagnostic labels naming the pathological structure (Sahrmann, 2014).

3. From research to practice

In a welcome attempt to ensure clinical practice is more scientifically and empirically grounded, the role of evidence based medicine has grown significantly over the last decades (Greenhalgh, Howick, & Maskrey, 2014). There is increasing consideration in the literature for the contribution of specific characteristics of altered movement variables resulting in the emergence, continuation and/or recurrence of pain and pathology, hereby supporting the kinesiopathological model. The relationship between movement and pathology is based on a combination of (i) cross-sectional studies relating different movement patterns with loading of specific anatomic structures or body regions (Dingenen et al., 2015b; Meardon & Derrick, 2014; Meardon, Campbell, &

Derrick, 2012; Oyama et al., 2014; Solomito, Garibay, Woods, Ounpuu, & Nissen, 2015; Willson, Ratcliff, Meardon, & Willy, 2015), (ii) retrospective studies showing maladaptive movement patterns in pathological populations (Allison et al., 2016; Ferrari et al., 2017; Franklyn-Miller et al., 2014, 2017; Luomajoki, Kool, de Bruin, & Airaksinen, 2008; Nakagawa, Moriya, Maciel, & Serrao, 2012; Neal, Barton, Gallie, O'Halloran, & Morrissey, 2016; Pappas, Zampeli, Xergia, & Georgoulis, 2013; Pohl, Mullineaux, Milner, Hamill, & Davis, 2008; Van Hoof, Volkaerts, O'Sullivan, Verschueren, & Dankaerts, 2012), (iii) prospective studies showing alterations in movement patterns in those persons who sustain injuries (Dingenen et al., 2015a, 2016; Hewett et al., 2005; Hickey, Solvig, Cavalheri, Harrold, & McKenna, 2017; Holden, Boreham, Doherty, & Delahunt, 2017; Leppanen et al., 2017; Myer et al., 2010; Noehren et al., 2007, 2013; Numata et al., 2017; Paterno et al., 2010; Roussel et al., 2009; Schuermans, Van Tiggelen, Palmans, Danneels, & Witvrouw, 2017; Stefanyshyn, Stergiou, Lun, Meeuwisse, & Worobets, 2006; Verrelst et al., 2014) and (iv) intervention studies showing improved clinical outcomes and decreased injury risk with specific training programs focusing on improving movement patterns (Barton et al., 2016; Donnell-Fink et al., 2015; Savoie, Mercier, Desmeules, Fremont, & Roy, 2015; Struyf et al., 2013; Worsley et al., 2013). Nevertheless, this complex relationship between movement and pathology is far from conclusive and only beginning to be understood in the literature (Hodges & Smeets, 2015; McQuade, Borstad, & de Oliveira, 2016).

However, from the clinician's point of view, some concerns can be formulated based on the majority of study designs currently used within this evidence-based approach. One major question arising is whether group-based average results emerging from clinical trials can be translated to the individual with a highly specific clinical presentation (Greenhalgh et al., 2014). This consideration highlights problems of the interpretation of the "mean value" as it can often flatten out the individual case. Everyone moves differently and a degree of variability in movement patterns is both "normal" and regarded as an important marker of movement health (Hamill, Palmer, & Van Emmerik, 2012; Kiely, 2017). The presence of variability makes evaluating movement patterns within and between individuals challenging. However, the high degree of variability within and between individuals does not implicate that a specific movement pattern may not be clinically relevant for an individual.

A general concept of an ideal or "normal" way to move probably doesn't exist. Given the multifactorial nature and intrinsic variability of human movement behavior, a "one size fits it all" approach to its subsequent management appears unwarranted. Rather, movement may be highly idiosyncratic, diverging from any normative values yet still efficient by ensuring functional tasks are able to be performed in a sustainable manner (Comerford & Mottram, 2012). Considering pathological and non-pathological groups as two distinct homogeneous groups may therefore fail to detect individual relevant alterations in movement. Likewise, an average treatment effect, which is the primary outcome of most clinical trials, may be diluted by the inclusion of a continuum of groups of patients or individuals for whom the average treatment approach is not effective (Foster, Hill, & Hay, 2011), hereby again hampering the transfer from research to clinical practice.

Another limitation in the literature is that multifactorial pathological conditions or an individual's functional capacity are often considered within a reductionist perspective, hereby focusing solely on very specific parts of an individual subsystem of the body (e.g. the movement system) in an attempt to explain or understand a clinical phenomenon or function of a person as a whole (Bittencourt et al., 2016). The individual, environmental and task-specific context of this evaluation is often neglected, which can lead to flawed clinical decision-making. Given the multidimensional nature of the human movement system, the use of multifactorial and complex models is warranted in future studies (Bittencourt et al., 2016).

Furthermore, most previous studies relating movement patterns to musculoskeletal injuries have largely neglected the role of workload (Windt & Gabbett, 2017). There is emerging evidence that athletes who experience a spike in workload for which they are not prepared for (e.g. expressed as a high acute/chronic workload ratio), are at increased risk of injury (Gabbett, 2016). Moller et al. (Moller et al., 2017) were the first to examine the relationship between internal risk factors, workload and shoulder injury risk in a group of 679 elite youth handball players. These authors found that scapular dyskinesis and a decreased external rotational strength of the shoulder exacerbated the effect of a rapid increase in training load on shoulder injury risk. As such, a state of less optimal movement health may decrease the ability to tolerate an increase in workload before an injury occurs. These findings support the models of Windt & Gabbett (Windt & Gabbett, 2017) and Nielsen et al. (Nielsen et al., 2017) where intrinsic and extrinsic risk factors are integrated with the effects of the application of workload on injury risk, hereby further reinforcing the need to use a multidimensional approach.

4. The role of a physical therapist

According to the 2013 House of Delegates American Physical Therapy Association's vision statement, the movement system is the core of the professional identity of physical therapists (American Physical Therapy Association, 2013). The physical therapist is responsible for evaluating and managing an individual's movement system across the lifespan to promote optimal development, diagnose impairments, activity limitations and participation restrictions and provide interventions targeted at preventing or ameliorating activity limitations and participation restrictions (American Physical Therapy Association, 2013). Based on this professional identity of a physical therapist, the ability to evaluate movement is now becoming the cornerstone to customize a targeted functional individual plan of care, improve movement health, maximize functional capacity and reach individual goals on the short and on the long term (American Physical Therapy Association, 2013). Key to managing individual movement impairments is a thorough understanding of human movement and the ability to identify changes in movement coordination strategies with a clinical assessment, followed by a comprehensive clinical reasoning process within a multidimensional perspective.

Many clinicians and researchers have proposed a variety of movement classification approaches in literature to assist the evaluation of movement health in clinical practice (Comerford & Mottram, 2012; Hewett & Bates, 2017; O'Sullivan, 2005; Sahrmann, 2002; Sahrmann, 2011). Despite the different opinions, terminology and clinical guidelines employed, in general they support each other's philosophies and provide different pieces of the bigger movement health puzzle (Comerford & Mottram, 2012).

5. Movement evaluation model

As outlined earlier, the assessment methods presented in the current masterclass will not focus upon the multiple factors influencing movement (Table 1) but will evaluate characteristics of the movement outcomes. Any systemized approach to the assessment of movement must be cognizant of the inherent variability evident within the human movement system (Hamill et al., 2012). Indeed, acknowledging "we all move differently" presents the clinician with a challenge in evaluating an individual current state of movement health. In light of this perspective, there is then the need for clarification of the differing levels of movement variability and their interpretation. Preatoni et al. (Preatoni et al., 2013) distinguish outcome variability (the consistency in what is achieved, e.g. step length during running) from coordinative variability (the range of coordinative strategies exhibited while performing this outcome). Both types of variability can be further classified as high or low. Traditionally, high outcome variability has been viewed as undesirable, as expertise is aligned to consistency in the achievement of a movement outcome (Ericsson & Lehmann, 1996). However, in terms of coordinative variability, an opposite interpretation has been formulated in the literature (Hamill et al., 2012). High coordinative variability can be advantageous for the performance of functional tasks such as activities of daily living, occupational and sports related skills (Hamill et al., 2012). Low coordinative variability has been associated to overuse injuries, as the same tissues are stressed in the same way or the interval between tissues being exposed to stress is diminished (Hamill et al., 2012). However, too much coordinative variability may be indicative for decreased movement health as well (Hamill et al., 2012). This leads to the assumption that there is a "window" of variability in which healthy individuals function (Hamill et al., 2012). The decreased ability to reorganize and adapt to the changing task and environmental constraints is a growing area of interest for both researchers and clinicians (Dingenen & Gokeler, 2017; Hodges & Smeets, 2015; Kiely, 2017; Preatoni et al., 2013; Wikstrom et al., 2013).

The Movement Evaluation Model proposed within the current masterclass is considerate of individual movement variability supporting a case by case approach. We propose a distinction between the evaluation of a spontaneous observed movement pattern (preferred or natural movement behavior) and cognitive movement control evaluation, based on a combination of a thorough consideration of current scientific literature on human movement control, clinical experience and comprehensive clinical reasoning processes.

5.1. Preferred or "natural" movement evaluation

During the preferred or "natural" movement evaluation, tasks such as running, jumping, squatting, sit-to-stand, one-leg stance, throwing or other activity- or sport-specific movements can be performed without any prior specific instruction how exactly to perform the task in terms of quality of movement. For example, during a drop vertical jump, an athlete is instructed to drop off a box and jump up as high as possible in a vertical direction after the first landing (Fig. 2). No further instructions are provided. The preferred or natural way to perform the jump-landing task is measured or observed. These tasks are generally thought to possess a high correlation to the activities and joint loading encountered during daily living or sport activities and are therefore often argued to be functional tests (Ortiz & Micheo, 2011). The basic premise of this form of evaluation is to have an indication on the movement and joint loading patterns of a person which will interact with the workload and the structure-specific load capacity to produce a structure-specific cumulative load (Nielsen et al., 2017).

Biomechanical studies have evaluated the effects of forces acting on or being produced by the body during these "functional" movements through measurement techniques such as kinematic and kinetic analyses which may vary according to the specific research question (Riemann, Myers, & Lephart, 2002; Winter 2009). Kinematic analyses are used to describe the details of human movement, but are not concerned with the forces that cause the movement (Winter 2009). The kinematic outcomes can include linear and angular displacements, velocities or accelerations (Winter 2009). Different devices exist to measure human body

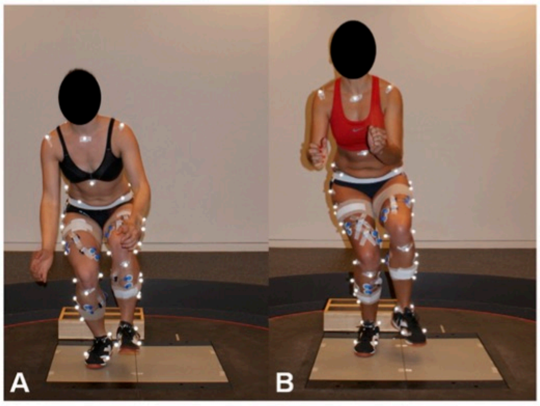

Fig. 2. An example of two different persons (A–B) performing the single-leg drop vertical jump.

kinematics, including video analysis and opto-electronic systems (Shumway-Cook, 2007). Kinetic analyses study the forces that cause the movement, including both internal and external forces (Shumway-Cook, 2007). Internal forces come from structures within the body, such as muscle activity or ligaments. External forces come from the ground or external loads such as gravity (Shumway-Cook, 2007). Ground reaction forces and kinematics are often measured synchronously to calculate the joint moments from equations that consider the segments of the limb, the joint position, and the location, magnitude and direction of the ground reaction forces (Sigward et al., 2012).

From a historical point of view, these movement assessments have mainly focused on isolated single-planar evaluation of one joint (e.g. knee flexion), or one body region (e.g. flexion-extension of the low back). This local approach was mostly directed towards evaluating the painful or pathological joint or body region in persons with pain or pathology. However, it is increasingly recognized that the human body functions as an integrated series of highly interacting multiple segments across multiple planes within a "kinetic chain" (Dingenen et al., 2014, 2015b; Kibler, Wilkes, & Sciascia, 2013; Mendiguchia, Ford, Quatman, Alentorn-Geli, & Hewett, 2011; Powers, 2010). The term "kinetic chain" originates from an engineering background in the 19th century and refers to a conceptual framework where the body is considered as a linked system of interdependent segments to achieve the desired movement in an efficient manner (Karandikar & Vargas, 2011; Mendiguchia et al., 2011; Putnam, 1993). Each segment in a linked system influences the motions of its adjacent segments in a way that is dependent on how the segment is moving and how the segment is oriented relative to its adjacent segments (Putnam, 1993). The application of an external force causes each segment to receive and transfer force to the adjacent segment, generating a chain reaction (Karandikar & Vargas, 2011). As such, the term kinetic chain is used to describe both kinematic and kinetic linkages (Kibler et al., 2013). Based on this kinetic chain concept, repetitive overloading of specific tissues or even a specific acute peripheral joint injury is often the end result of a combination of individual-specific interactions of movements in different planes at different points within the kinetic chain. Focusing only on one particular segment may lead to underestimations of the relevance of movement impairments for an individual. Multi-segmental and multi-planar movement assessment approaches are therefore probably more representative of real-life situations.

A limitation of the currently used biomechanical evaluation approach is that most scientific information is based on measurements performed in laboratory settings. Despite the fact that the information coming from complex laboratory settings is highly valuable to increase our knowledge on the value of movement, these methodologies have two main limitations. First, the measurements used are often hard to apply in clinical settings where the same laboratory equipment is not available. In this perspective, the development of reliable and valid clinical-oriented methodologies such as two-dimensional video analysis (Dingenen et al., 2015a, 2018) and clinical observation scales (Crossley, Zhang, Schache, Bryant, & Cowan, 2011; Fort-Vanmeerhaeghe, Montalvo, Lloyd, Read, & Myer, 2017; Padua et al., 2009; Whatman, Hume, & Hing, 2013) is promising. The technological development of “wearables” offers now a tremendous opportunity to bring the lab to the field and measure movement in real-life environments. This might offer a potential solution for the second limitation, where one may question whether the findings coming from highly controlled laboratory and clinical environments are truly representative for the real-life environments (Dingenen & Gokeler, 2017), hereby acknowledging the importance of the environmental and task constraints within the dynamic system theory (Davids et al., 2003; Holt et al., 2010; Newell, 1986; Wikstrom et al., 2013). For example, trunk and lower limb mechanics can be significant different during unplanned athletic activities compared to planned activities (Brown et al., 2014). This might be particularly relevant for athletes who are confronted with quick and unplanned movements during sport-specific activities, based on increased temporal and visuospatial environmental constraints (e.g. reacting on a sudden action of another player, or movement of a ball).

Human movement variability is inherent and essential during preferred movement, and as a consequence also during the evaluation of preferred biomechanics. No repetition will exactly be the same than the previous one. As a consequence, clinicians are advised not to make clinical interpretations based on a single repetition of a certain task. However, the exact number of repetitions needed to have an appropriate outcome measure is not straightforward and dependent on the activity, the subject and the variable under investigation (Preatoni et al., 2013). To be able to interpret this variability between different repetitions of a given task of the same individual, the environment should be taken into account. Too much coordinative variability between consecutive repetitions within a consistent environment (e.g. running on a flat surface) may indicate a less optimal cooperation between the different components of the dynamic system theory, resulting in less efficient movement (Harbourne & Stergiou, 2009; Kiely, 2017). For example, Pollard et al. (Pollard, Stearns, Hayes, & Heiderscheit, 2015) showed that female athletes with an anterior cruciate ligament reconstruction who returned to full sport participation had an increased coordinative variability during a side-stepping task compared to non-injured controls. On the other hand, when the environment is less consistent or predictable (e.g. running on a surface with obstacles or catching a ball), it is imperative that the movement strategies are adapted to the environment. Several studies have shown across different populations that persons with pain, (previous) injury or older age have a decreased ability to adapt their movement coordinative strategies according to changing environmental and/or task constraints (Chiu & Chou, 2012; Grooms et al., 2015; Hodges & Smeets, 2015; Wikstrom et al., 2013). The alterations across both ends of the spectrum of movement coordinative variability may lead to a reduction in the number of movement strategies available for an individual to efficiently responding to specific tasks or environments (Glasgow, Bleakley, & Phillips, 2013). A graphical summary of the relationship between the variability of coordination strategies during preferred movements during a given task and the environmental constraints is presented in Fig. 3, hereby emphasizing the role of the previously mentioned more advantageous window of variability in movement coordination strategies.

Different methods have been proposed to estimate coordinative variability of kinematic or kinetic outcomes during preferred movement evaluations. The use of non-parametric estimators of spread (e.g. interquartile range or median absolute deviation) are advised when evaluating discrete outcomes (e.g. peak hip adduction) (Preatoni et al., 2013). Discrete outcomes are easier to evaluate in daily clinical practice, but one should be aware that this approach might provide only a limited insight in the coordinative variability across the whole movement cycle (Preatoni et al., 2013). Irrespective of which methodology is used during evaluation, the clinical interpretation in function of the individual person within a multidimensional context remains essential (Dingenen & Gokeler, 2017). Based on this clinical interpretation, a certain preferred movement pattern can then be considered as biomechanically more or less advantageous for a particular person at a particular point in time.

5.2. Cognitive movement control evaluation

Cognitive movement control assessment evaluates an individual's ability to cognitively coordinate movement at a specific joint or region (site) in a particular plane of movement (direction), under low and high threshold loading often during multi-joint tests within functionally orientated tasks (Comerford & Mottram, 2012; Mischiati et al., 2015; Monnier, Heuer, Norman, & Ang, 2012). These tests have been employed with a focus on different body regions such as the shoulder (Rajasekar, Bangera, & Sekaran, 2017), cervical spine (Patroncini, Hannig, Meichtry, & Luomajoki, 2014; Segarra et al., 2015), lumbo-pelvic complex (Luomajoki & Moseley, 2011; Luomajoki et al., 2007, 2008), hip (Lenzlinger-Asprion, Keller, Meichtry, & Luomajoki, 2017) and lower extremity (Mischiati et al., 2015) within a range of populations including non-injured athletes (Olivier, Stewart, Olorunju, & McKinon, 2015; Roussel

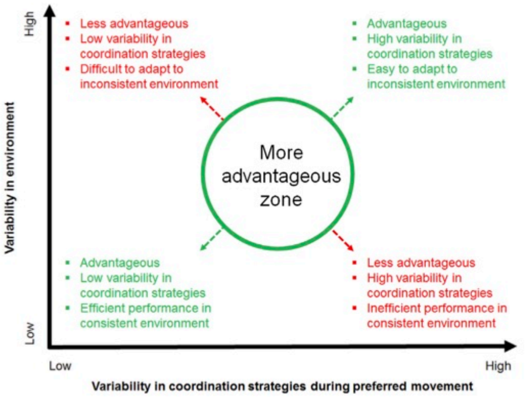

Fig. 3. The relationship between coordinative variability during preferred movement (x-axis) and the variability in the environment (y-axis). The green circle in the middle reflects a more advantageous zone of movement coordinative variability. Both too high and too low coordinative variability might be less advantageous, especially during respectively consistent and less consistent environments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2009), persons with pain (Corkery et al., 2014; Lenzlinger-Asprion et al., 2017; Luomajoki & Moseley, 2011; Luomajoki et al., 2008), and persons with a history of pain (Monnier et al., 2012). Described in detail elsewhere (Comerford & Mottram, 2012; Luomajoki et al., 2007; Mischiati et al., 2015; Mottram & Comerford, 2008) these tests have demonstrated good to excellent inter- and intra-rater reliability (Lenzlinger-Asprion et al., 2017; Luomajoki et al., 2007; Mischiati et al., 2015; Patroncini et al., 2014; Rajasekar et al., 2017; Segarra et al., 2015).

During function, whilst it is rare for movement to be either eliminated at one joint system while moving at another, or to move in one plane only, the ability to consciously coordinate the body's degrees of freedom in this manner can be used as test of movement control. This protocol can be seen to identify the presence of uncontrolled movement, defined as "an inability to cognitively control movement at a specific site and direction while moving elsewhere to benchmark standards" and can be representative of a loss of choice in coordinative strategies (Comerford & Mottram, 2012). These cognitive movement control tests possess both a clearly defined starting alignment and end position, representing benchmarks which must be consistently achieved at both the initiation and completion of each test's performance. During the test, the movement coordination strategy employed to achieve these benchmarks are both observed and evaluated (Mottram & Comerford, 2008). A person is asked to consciously attempt to prevent any observed uncontrolled movement. This questioning of the ability to vary the test's performance introduces a cognitive element to the testing, informing upon the individual's movement coordinative variability capacity.

For example, during the double knee swing test, the start position is a small knee bend. The person is asked to maintain a neutral lumbo-pelvic position and to swing both knees in tandem from side to side, allowing the feet to roll into supination and pronation but keep all metatarsal heads on the floor (Fig. 4) (McNeill, 2014). The benchmark dictates that the knees have to reach 20° to each side from the midline. The ability to control the pelvis during this test demonstrates efficient cognitive movement control at this site (pelvis) and direction (rotation). If other coordination strategies are observed (e.g. rotation of the pelvis to the left or right) during this cognitive movement control test, this demonstrates inefficient cognitive movement control at this site and direction.

Arguably the more coordinative strategies an individual can display to achieve a movement outcome the greater the possession in the choice of movement, a key element in movement health. Failing a movement control test demonstrates loss of choice on how the movement outcome is achieved. We consider this as inefficient cognitive movement control and a compromised state of movement health. This loss of choice/uncontrolled movement (inefficiency) is evident as an inability to achieve the benchmarks of cognitive movement control testing and can be labeled with the site, direction and the threshold of muscle recruitment at which they manifest (Mottram & Comerford, 2008). Testing with respect to the threshold of motor unit recruitment is suggested to reveal the movement "choices" consistently employed during postural and non-fatiguing tasks (low threshold recruitment) and those in which fatiguing load and speed are present (high threshold recruitment). As these different loading/intensity environments are influenced by different physiological mechanisms, testing is suggested to inform on loss of movement choices and the presence of low movement coordinative variability across a spectrum of tasks. The ability to pass a battery of cognitive movement control tests in all planes of movement illustrates a desirable wealth of choice in movement options (high movement coordinative variability).

Fig. 4. Double knee swing to the right (A) and left (B).

5.3. Interpretation and implication of the movement evaluation model

The proposed Movement Evaluation Model blends the analysis of the preferred (or natural) movement strategy (more or less biomechanically advantageous) with cognitive movement control evaluation (efficient or inefficient) in our clinical journey to understand and interpret the influence of multiple constraints and their interactions impacting movement health (Table 2). The purpose of the integration of the distinct characteristics of the two assessment methods within this model is not to provide a concept to predict injuries, but to present a multidimensional approach to assist the identification of movement control strategies to assess movement health from a clinical perspective. Based on the classification within our framework (group A, B, C or D), an appropriate combination and sequencing of movement control retraining and functional performance retraining can be developed (Table 3). We acknowledge that this classification is a basic framework to support clinical reasoning within a person-centered approach, and again, emphasize that movement should be interpreted within a broad and multidimensional perspective. Since this is the first time this framework is presented, future studies should further evaluate its clinical validity. We hypothesize that clinical outcomes can be improved when interventions are targeted to the specific individual presentation. In addition, future studies should further explore and refine the approaches to optimize motor learning (Benjaminse et al., 2015; Wulf & Lewthwaite, 2016).

6. Conclusion

In this masterclass we have provided an overview of the role of movement health and contemporary approaches to evaluate movement. The Movement Evaluation Model focuses on the measurable movement outcome of resultants on numerous interactions of individual, environmental and task constraints. The model uses tests of preferred movement biomechanics and a battery of cognitive movement control tests to assist clinical

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Table 2
A framework presenting 4 different groups, based on the performance on both the preferred movement and cognitive movement control evaluation.

		Preferred movement evaluation ("natural" functional movement biomechanics)	
		Biomechanically advantageous strategies	**Biomechanically less advantageous strategies**
Cognitive movement control coordination & efficiency	Efficient movement control	**Group A** + +	**Group B** - +
	Inefficient movement control	**Group C** + -	**Group D** - -

Table 3
Description of the Movement Evaluation Model with interpretations and recommendations.

Group A: More advantageous biomechanics & efficient cognitive movement control	**Group B: Less advantageous biomechanics & efficient cognitive movement control**
Description: This group demonstrates more advantageous preferred movement strategies and pass a battery of movement control tests. They display an ability to rapidly learn and reproduce technique skills. Technique correction with coaching is easily achieved and integrated into more complex movement skills. **Interpretation:** • Ability to optimize advantageous biomechanics with movement training – **effective** • Potential to improve "technique" with coaching – **high potential** • Performance deficiency or functional impairment – **minimal impairment** • Potential to optimize performance – **high potential** • Potential to enhance robustness with structured loading – **high potential** • Likelihood to exceed intrinsic tissue tolerance with overload training – **low** **Recommendation:** This group can prioritize skill and technique development with functional training strategies.	**Description:** This group demonstrates less advantageous preferred movement strategies but pass a battery of movement control tests. They possess movement control choices to vary performance and can quickly improve function and performance by employing movement strategies during training and skill optimization. Variability in movement control options allows effective progressions in coaching and skill development training. **Interpretation:** • Ability to improve less advantageous biomechanics with movement training – **reasonably effective** • Potential to improve "technique" with coaching – **moderate potential** • Performance deficiency or functional impairment – **moderate impairment** • Potential to optimize performance – **moderate potential** • Potential to enhance robustness with structured loading **– moderate potential** • Likelihood to exceed intrinsic tissue tolerance with overload training – **moderate** **Recommendation:** This group should prioritize biomechanical optimization and skill development with training. However, functional training should progress in structured and controlled progressions with an emphasis on technique and performance skills optimization.
Group C: More advantageous biomechanics & inefficient cognitive movement control	**Group D: Less advantageous biomechanics & inefficient cognitive movement control**
Description: This group demonstrates more advantageous preferred movement strategies but fail a battery of movement control tests. The advantageous habitual movement strategies are typically present in a limited set of functional tasks and skills and/or only in one plane of movement (e.g. sagittal plane). Inefficient control of specific movements indicates reduced variability of movement control options, which has implications for reduced robustness of tissues under load and potential to exceed tissue tolerance. They have problems controlling movement during a variety of tasks, multidirectional challenges in sport or when their attention is focused elsewhere. Inefficient control of specific movements may impact on the ability for technical or performance skill training to develop effectively and to progress quickly. **Interpretation:** • Ability to optimize advantageous biomechanics with functional movement training – **effective** • Potential to improve "technique" with coaching – **moderate potential** • Performance deficiency or functional impairment – **minimal impairment** • Potential to optimize performance – **moderate potential** • Potential to enhance robustness with structured loading **– low potential** • Likelihood to exceed intrinsic tissue tolerance with overload training – **moderate** **Recommendation**: This group would benefit from cognitive movement control training to optimize recruitment synergies to "fast track" skill development with functional training.	**Description:** This group demonstrates less advantageous preferred movement strategies and fail a battery of movement control tests. They will struggle to optimize biomechanics in functional activities or performance skills with functional training only. Inefficient movement control and reduced variability of movement options impairs the ability to improve technical skills and alter less advantageous biomechanics. This group is more likely to significantly increase tissue loading and exceed tissue tolerance with repetitive or overloaded movements in functional activities and sport. **Interpretation:** • Ability to improve less advantageous biomechanics with functional movement training alone – **ineffective** • Potential to improve "technique" with coaching – **limited potential** • Performance deficiency or functional impairment – **significant impairment** • Potential to optimize performance **– limited potential** • Potential to enhance robustness with structured loading **– low potential** • Likelihood to exceed intrinsic tissue tolerance with overload training **– high** **Recommendation**: This group would benefit from cognitive movement control training to improve ability to control the site and direction of uncontrolled movement prior to skill development. By training movement control a more optimal degree of movement variability can be established. This will enhance robustness and accelerate the ability to show improvements in functional activities and performance skill retraining.

judgement as to how to best improve movement health across an individual lifespan. The proposed content of the current master-class may help to interpret clinical findings from movement assessment, guide treatment, facilitate communication between and within clinicians and researchers and promote a modern kinesiopathological approach within a multidimensional perspective whereby clinical reasoning skills of a physical therapist are essential.

Conflict of interest statement

Sarah Mottram and Lincoln Blandford are employees of and Mark Comerford is a consultant to Movement Performance Solutions Ltd, which educates and trains sports, health and fitness professionals to better understand, prevent and manage musculoskeletal injury and pain that can impair movement and compromise performance in their patients, players and clients. None of the other authors have any conflict of interest to declare.

Ethical approval

None declared.

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Masterclass

Assessment of movement coordination strategies to inform health of movement and guide retraining interventions

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ABSTRACT

Introduction: Exploring characteristics of human movement has long been the focus of clinicians and researchers. Changes in movement coordination strategies have been identified in the presence of pain highlighting the need for assessment in clinical practice. A major development in the understanding of movement related disorders is recognition of individual differences in presentation and consequently the need to tailor interventions based on assessment.

Purpose: The purpose of this masterclass is to build a rationale for the clinical assessment of movement coordination strategies, exploring loss of movement choices, coordination variability, and to present a clinical framework for individualised management, including the use of cognitive movement control tests and retraining interventions. An approach for the qualitative rating of movement coordination strategies is presented. A compromised movement system may be one characterised by a lack of ability to access motor abundance and display choice in the use of movement coordination strategies. The identification of lost movement choices revealed during the assessment of movement coordination strategies is proposed as a marker of movement health.

Implications for practice: The health of the movement system may be informed by the ability to display choice in movement coordination strategies. There is evidence that restoring these choices has clinical utility and an influence on pain and improved function. This approach seeks to provide individuals with more flexible problem solving, enabled through a movement system that is robust to each unique challenge of function. This assessment framework sits within a bigger clinical reasoning picture for sustained quality of life.

1. Introduction

The value of movement is central to the Physical Therapy profession and exploring the varying characteristics of human movement is the focus of clinicians and researchers (Sahrmann, 2002; Hides et al., 2019; Everard et al., 2018; Shield and Bourne, 2018). Exploration of motor control, prevalent in the last 25 years, has led to numerous terms being advocated, for example neuromuscular control, neuromotor control, and core stability, leading to debates over terminology and conceptual explanations in clinical practice, education, and research (Low, 2018). A major development in the understanding of movement related disorders, is recognition of individual differences in presentation and the need to tailor interventions based on assessment (Van Dieen et al., 2019; Falla et al., 2007).

A recent commentary presented key principles of four clinical physical therapy approaches, Movement Systems Approach, Mechanical Diagnosis and Therapy, Motor Control Training, and the Integrated Systems Model (Hides et al., 2019). All approaches incorporated detailed assessment to guide individualised treatment, but elements addressed differed. Although these approaches focussed on the evaluation of movement, they did not explore an individual's ability to display choice in their patterns of movement coordination strategies (Dingenen et al., 2018). The present paper, by two of the authors of Dingenen's Masterclass (Dingenen et al., 2018), will explore the concept of displaying choice in movement coordination strategies and its use in a clinical setting.

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Pain, pathology, compromised function and the many dynamic and interacting factors that may be associated with any presentation, make the management of each patient complex (Bittencourt et al., 2016; Hides et al., 2019). Acknowledging the role movement assessment and retraining may play in the clinical environment, Dingenen et al. (2018) proposed a version of the dynamical systems model, Fig. 1, adapted from Holt et al. (Dingenen et al., 2018; Holt et al., 2010). The model represents human movement as the observable response to opportunities and challenges posed by the continual interaction of what Newell identified as task, environmental and individual constraints (Newell, 1986). Dingenen et al. (2018) emphasised placing a clinical focus on the assessment of the movement emerging from these interactions, described as movement coordination strategies, in contrast to focusing upon any particular constraint, for example pain, myofascial restriction or a pathoanatomical structure (Dingenen et al., 2018). Dingenen et al. (2018) proposed that one aspect of assessing movement coordination strategies was to evaluate loss of movement choices, which has been proposed as a marker of movement health (McNeill and Blandford, 2015). The authors of the present paper have experience in the practical application of these assessment and retraining strategies in clinical and performance environments, and research interests in this subject which are reflected in this Masterclass.

The purpose of this masterclass is to build a rationale for the clinical assessment of movement coordination strategies, exploring loss of movement choices, coordination variability, and present a clinical framework for individualised management, including the use of cognitive movement control tests and retraining interventions. The first part of the masterclass presents the concept of movement coordination strategies, explores movement quality including movement as problem solving, movement variability, movement health and choice in movement. The second part presents a clinical framework to explore loss of movement choices through testing patterns of movement coordination strategies with CMCTs. The assessment procedure is detailed including the neutral training region and single joint and multi-joint testing with practical illustrations. Retraining by restoring movement choices is outlined. Finally, this is placed into a clinical reasoning context.

2. Movement coordination strategies

Technological innovations, allowing the capture, interpretation and targeting of kinetic and kinematic measures have had a positive impact on clinical outcomes (Al Attar et al., 2017; King et al., 2018; Worsley et al., 2013). King et al. (2018) and Worsley et al. (2013) used kinematic assessment of a functional task (cutting manoeuvre and arm elevation, respectively) to demonstrate the effectiveness of retraining intervention protocols. However, these papers did not use kinematic measures to steer retraining. Therefore, kinematics were employed as an outcome measure, but not as a means to guide interventions. Whilst the utility of the retraining interventions can be translated into clinical practice, the quantification of movement in clinical environments is challenging because of the associated financial and technical burdens. In addition to showing retraining interventions change kinematic measures, a proof of context case report illustrates that assessment of movement coordination strategies can also inform the direction and effectiveness of individualised retraining programmes (Mottram et al., 2019). King et al. (2018) and Worsley et al. (2013) included the characteristics of movement that meet the description of coordination as defined by Kent (2006) in retraining interventions; i.e. the integration of different body parts during the performance of a specific movement pattern (Kent, 2006). It is apparent that coordination refers to more than this observable change in configuration of body parts (Nordin and Dufek, 2019; Kent, 2006) but also intra and intermuscular activation dynamics (Hug and Tucker, 2017; Hawkes et al., 2019) in addition to consideration of the cognitive and perceptual processes linked to the generation of movement coordination strategies (Newell, 1986; Raisbeck and Yamada, 2019). Therefore, this observable characteristic of movement (coordination) is influenced by multiple elements further supporting the value of evaluating the movement coordination strategy. In the absence of technology, a clinically applicable approach to evaluating movement coordination strategies is presented.

2.1. Movement quality

Movement quality has been described as qualitative identification and rating of functional compensations, asymmetries, impairments or efficiency of movement control through transitional (e.g. squats, sit to stand) or dynamic movement (e.g. running, landing, cutting) tasks (Whittaker et al., 2017). Some movement quality protocols seek to rate an individual's patterns of coordinated movement against a predetermined 'template' with observable deviations from this model rated as aberrant/error and requiring correction (Cook et al., 2014; Padua et al., 2011). The Landing Error Scoring System evaluates movement

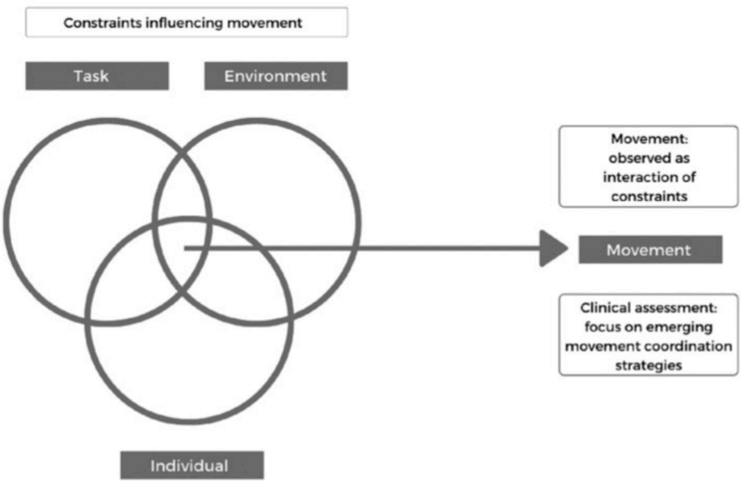

Fig. 1. Movement is influenced by an interaction of constraints of the task, individual and environment.

quality during jump-landing and changes in movement quality been associated with anterior cruciate ligament injury (Padua et al., 2015). The movement quality perspective has received criticism, from those questioning whether any movement can be considered aberrant (Guccione et al., 2019). Guccione et al. (2019) suggest the phenomenon of movement represents a problem-solving property, employed by individuals to accommodate the challenges presented by numerous constraints.

2.1.1. Movement as problem solving

A major challenge for qualitative rating of movement as a biomarker is the lack of clear definitions for optimal task performance (Glazier and Mehdizadeh, 2019; Konig et al., 2016). When movement is perceived as a problem-solving phenomenon, it appears individuals solve problems through varying solutions in response to a perpetual state of changing demands between and within constraints to achieve a consistent outcome (Davids et al., 2003; Guccione et al., 2019). Motor redundancy, now reconceptualised as 'motor abundance', supplies the potential for this problem solving, facilitating a consistent task outcome (Bernstein, 1967; Davids et al., 2003; Latash, 2012). Rather than the existence of a single 'optimal' strategy, to respond to changing demands, it appears individuals find a 'good enough' solution (Loeb, 2012). The use of a wide range of solutions may allow the stresses of function to be shared across a range of tissues (Bouillard et al., 2014; Blandford et al., 2018a; James et al., 2014).

Characteristics of movements are seen to change in clinical populations (Hodges and Smeets, 2015), for example changes in kinematics are seen in the presence of pain and injury (Christe et al., 2017; Dingenen et al., 2019). These altered movement coordinated strategies may illustrate altered problem solving and may be linked to specific constraints. Although distinctions between groups are identifiable, there is a lack of consensus as to whether metrics that reach statistical significance possess clinical relevance, and perhaps other characteristics of movement should be explored.

2.1.2. Movement variability

Defined as the variation in motor performance over multiple repetitions of a task (James et al., 2000), movement variability has been explored in clinical presentations including, acute injury and pain (Seay et al., 2011; Weir et al., 2019), overuse injury (Hamill et al., 2012), injury recurrence (Edwards et al., 2017; Davis et al., 2019), pathology (Kawakami et al., 2019) and aging (Hausdorff et al., 2001). Therefore, movement variability is of interest to the clinician. The degree of movement variability may be a marker of a robust movement system, a theme apparent within clinically focussed, coordination variability literature (Davis et al., 2019; Kawakami et al., 2019; Weir et al., 2019). Although these emerging papers are highlighting the importance of considering movement variability, currently there is little direct translation into the clinic in terms of assessment and rehabilitation. Interestingly, Kawakami et al. (2019) observed changes in coordination patterns at the rearfoot and midfoot is associated with forefoot hypermobility in people with hallux valgus, illustrating a mutlisegmental approach is needed in assessment and rehabilitation. Some authors have suggested the existence of an optimal window of variability (Konig et al., 2016; Harbourne and Stergiou, 2009) in which healthy subjects function. Clinical groups illustrate both reduced and increased coordination variability (Madeleine et al., 2008; Hodges and Tucker, 2011). Pain has been associated with increased coordination variability which may indicate a strategy used by people in pain to search for less painful movement patterns (Hodges and Tucker, 2011; Srinivasan and Mathiassen, 2012). Altered proprioception following injury is linked with increased coordination variability (Baida et al., 2018). Reduced coordination variability is suggested to be a risk factor for overuse injury (Nordin and Dufek, 2019; Hamill et al., 2012) but clinically also seen as a solution to minimise pain provoking movement coordination strategies. Coordination variability can be quantified in the laboratory using kinematic measures but is not clinically viable. There are calls for movement variability analysis to extend into routine clinical evaluations (Harbourne and Stergiou, 2009; Needham et al., 2015). This masterclass presents the use of cognitive movement control tests as a qualitative rating to inform on coordination variability by the assessment of movement coordination strategies within a clinical setting.

2.1.3. Movement health and choice in movement

The concept of movement health is defined as 'a state in which the individual is more than just injury free but possesses choice in their movement outcomes' and this is suggested to act as a marker of the current status of the movement system (McNeill and Blandford, 2015). Conceptually, individuals with a more robust state of movement health can sustain the achievement of any desired movement task by accessing the wealth of movement coordination strategies within motor abundance (Dingenen et al., 2018). A compromised movement system may be one characterised by a lack of ability to access motor abundance and display choice in the use of movement coordination strategies. The identification of lost movement choices revealed during the assessment of movement coordination strategies is a marker of movement health.

3. Testing patterns of movement coordination strategies/ movement choices

This present masterclass presents a clinical framework to explore loss of movement choices. The protocol demands a cognitive display of a movement task suggested to represent an individual's ability to access what motor abundance supplies, at will. An inability to vary a movement coordination strategy illustrates loss of movement choices. However, as this performance is accompanied by a lack of choice, it would infer the presence of the inflexible problem solving linked to overuse injury (Nordin and Dufek, 2019). Alternatively, an individual's performance that is characterised by both a constant variation in movement coordination strategy, and an inability to cognitively demonstrate precision, appears to represent the high variability associated with compromised neuromuscular regulation of movement (Baida et al., 2018). Rather than suggesting there is an ideal movement coordination strategy, the protocol seeks to reveal whether; i) an individual consistently employs one strategy that is invariant even when provided the opportunity to change or ii) constantly varies strategy but cannot demonstrate consistency in their performance if so required. This possession of choice of movement can be evaluated with cognitive movement control tests (CMCT).

3.1. Cognitive movement control tests for assessing patterns of movement coordination strategies

We propose that CMCTs allow for a qualitative rating of coordination variability that can be used to test movement coordination strategies. We put forward the term loss of movement choices (LMC) is used to inform on the inability to vary a movement coordination strategy. CMCTs demand an individual to cognitively coordinate movement at a specific joint or region (site) in a particular plane of movement (direction), under low and high threshold loading during single and multi-joint tests, while producing movement at another joint segment to a benchmark standard (Dingenen et al., 2018; Mischiati et al., 2015; Monnier et al., 2012; Wilson et al., 2018; Mottram and Comerford, 2008; Comerford and Mottram, 2012; Mottram et al., 2019; Botha et al., 2014; Roussel et al., 2009). These CMCTs ultimately seek to reveal what has been described as uncontrolled movement, defined as 'an inability to cognitively control movement at a specific site and direction, while moving elsewhere to benchmark standards' (Comerford and Mottram, 2012). Uncontrolled movement can be considered to represent LMC (loss of movement choices) and can be notated by the Site, Direction, Threshold ®. The site is the region e.g. hip, scapula, the direction is a physiological motion (for example, flexion, extension, rotation) and/or accessory motion (anterior translation), recruitment threshold is low or high (Dingenen et al., 2018; Mischiati et al., 2015). The reality is that it is impossible to prevent movement occurring at any joint or region; however, within clinical practice, an inability to cognitively prevent 'observable' movement at this site is deemed a loss of choice. This notation of Site, Direction and Threshold ® represents a clinical tool allowing loss of choice in movement coordination strategies to be qualified and considered within the bigger picture of clinical reasoning. The CMCTs are not tests of functional performance but are suggested to inform of loss of choice in movement. CMCTs have demonstrated good to excellent inter- and intra-rater reliability (Luomajoki et al., 2007; Mischiati et al., 2015; Rajasekar et al., 2017; Lenzlinger-Asprion et al., 2017; Segarra et al., 2015; Webb et al., 2018; Monnier et al., 2012).

3.2. Assessment procedure for cognitive movement control tests

The CMCTs described in the present paper follow clear principles of assessment procedure; a clearly defined start position, end position, and benchmark that must be achieved through the test. Examples include: Arm Flexion Test (Comerford and Mottram, 2012; Mottram, 2003), Kinetic Medial Rotation Test (Morrissey et al., 2008; Comerford and Mottram, 2012; Rajasekar et al., 2017), Small Knee Bend Test (Comerford and Mottram, 2012; Mischiati et al., 2015; Botha et al., 2014), Double Knee Swing Test (Comerford and Mottram, 2012; McNeill, 2014; Mischiati et al., 2015) and Split Squat and Fast Feet Change Test (Mischiati et al., 2015). Details of the principles of test procedures are set out in Table 1.

To set up a CMCT test, the individual is made aware of the required movement with visual, auditory and kinaesthetic cues. An opportunity to practice is provided, and feedback given. To pass the test, the individual must display the ability to consciously maintain the desired alignment at the region of interest (site and direction) whilst the region above or below, or the same joint in a different direction is actively moved to achieve a pre-determined benchmark. For example, Arm Flexion Test (Table 3); limiting observable movement of the site (scapula), whilst moving the glenohumeral joint into 90 degrees of flexion and return without observing scapular downward rotation (direction); or during Kinetic Medial Rotation Test (Table 4) limiting observable movement of glenohumeral joint (site), anterior translation whilst moving the glenohumeral joint into medial rotation.Test performance is observed and evaluated during both the achievement of the benchmark and its return (Mottram and Comerford, 2008; Comerford and Mottram, 2012).

3.2.1. Neutral training region

Testing with CMCTs requires the region of interest to be positioned in a neutral alignment. Fig. 2 represents the possible range the neutral position can sit within the three planes of movement. Rather than equating to 'ideal', the neutral alignment supplies the opportunity for a loss of movement choice to present in any available direction. If testing consistently began with the site of interest at end range, any loss of choice following this motion path would not be observed; low variability in coordination accompanied by a loss of choice would not appear. Additionally, in contrast to end range positions, which facilitate heightened joint sense position (Safran et al., 2001) a greater challenge may be imposed if the neutral alignment is required to be maintained. Such a challenge may then inform the presence of high coordination variability, suggested to accompany diminished proprioception (Baida et al., 2018).

Table 1
Cognitive Movement Control Test: Principles of procedure.

Cognitive Movement Control Test: Procedure	
Start position	Neutral training region
Teaching the test movement	Teach the test movement with varying strategies: • Visually demonstrate the test's 'shape' and movement • Verbally explain and describe the test movement and use of imagery • Facilitate/guide the person through the test movement
Active learning	Practice the movement with facilitation and feedback 3-8 repetitions are usually sufficient for facilitation and learning
Test	When confident that the person understands the test movement or action, perform the test to the benchmark, without visual or tactile feedback, verbal facilitation, or corrective instruction
Rating	On the test procedure, the therapists observe the performance of the test. Any observable uncontrolled movement is notated as site (X) and direction (X) of loss of movement choice

Table 2
Outline of five Cognitive Movement Control Tests.

Test	Identifies the Site, Direction, Threshold ® of loss of movement choices	Clinical Judgements
Table 3 (Single Joint) Arm Flexion Test (Comerford and Mottram, 2012; Mottram, 2003)	Site: scapula Direction: downward rotation Threshold: low	• Identifies uncontrolled scapula downward rotation associated with 'impingement type' symptoms (Worsley et al., 2013) • Kinematic differences between individuals noted on the test (Warner et al., 2015)
Table 4 (Multi-joint) Kinetic Medial Rotation Test (Comerford and Mottram, 2012)	Site: Scapula Direction: forward tilt Threshold: low Site: glenohumeral joint Direction: anterior Threshold: low	• Useful to identify primary loss of choice of scapula forward tilt or glenohumeral translation (Morrissey et al., 2008) • Reliability, (Rajasekar et al., 2017; Lluch et al., 2014; Mischiati et al., 2015)
Table 5 (both single joint and multi-joint) Small Knee Bend Test (Comerford and Mottram, 2012)	Site: hip Direction: flexion Threshold: low	• Clinical utility in academy footballers with femoroacetabular impingement syndrome (Botha et al., 2014) • Reliability (Mischiati et al., 2015)
Table 6 (Multi-joint) The Double Knee Swing Test (McNeill, 2014; Comerford and Mottram, 2012)	Site: low back and pelvis Direction: rotation Threshold: low Site: low back and pelvis Direction: side-bend Threshold: low Site: hip Direction: flexion Threshold: low Site: lower leg Direction: lateral rotation Threshold: low Site: foot Direction: eversion Threshold: low	• Identifies primary loss of movement choices at pelvis and leg on a rotary challenge • Clinical utility (Mottram et al., 2019) • Reliability (Mischiati et al., 2015)
Table 7 (Multi-joint) Split Squat and Fast Feet Change Test (Mischiati et al., 2015)	Site: low back and pelvis Direction: side-bend Threshold: high Site: hip Direction: flexion Threshold: high Site: hip Direction: medial rotation Threshold: high Site: tibia Direction: lateral rotation Threshold: high Site: foot Direction: inversion Threshold: high	• Identifies primary loss of movement choices at pelvis and leg on a sagittal challenge, with fast movement • Clinical utility (Mottram et al., 2019) • Reliability (Mischiati et al., 2015)

Table 3
Test description CMCT: Arm Flexion.

Arm Flexion Test	Tests for scapula control (scapular downward rotation)
Start position 	Standing, arm resting by side in neutral rotation (palm in), scapula in neutral. Maintain scapula as arm lifts through 90° of shoulder flexion then lower back to side.
Test movement 	Move: arm to 90° gleno-humeral joint flexion and return with a neutral humeral rotation (palm in, thumb up)
Benchmark:	90° gleno-humeral flexion – arm horizontal in front
Test pass	There is no observable movement of the scapula into downward rotation
Presence of loss of movement choice	Observable loss of scapula orientation into downward rotation

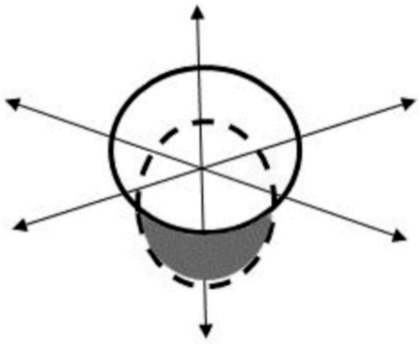

Fig. 2. The neutral training region. The solid circle represents the neutral position of a region within three planes of movement. The dotted line illustrates a change in the training region and the shaded area is outside the neutral position at or near the end of range.

3.2.2. *Single joint and multi-joint testing*

The protocol for CMCTs can be applied to both single joint and multi-joint testing (Comerford and Mottram, 2012; Mischiati et al., 2015). Single joint tests have been shown to have clinical utility, especially in the management of pain (Worsley et al., 2013; Luomajoki et al., 2008; Mottram et al., 2019). However, it is apparent individuals employ whole body movement coordination strategies, reducing variability at one region whilst increasing it at another (Edwards et al., 2017; Brown et al., 2012). Therefore, multi-joint testing protocols may allow for this dynamic problem-solving to be captured in a more ecologically relevant manner once pain is resolved (Mischiati et al., 2015; Mottram et al., 2019).

3.2.3. *Practical illustrations of cognitive movement control tests*

Five examples of CMCTs are described in Table 2 and protocols in Tables 3–7. The results of these CMCTs inform retraining priorities. Sites and directions of LMCs related to pain presentations are considered along with those related to performance. As movement represents a dynamic problem-solving phenomenon, these tests can be used to evaluate change over time.

4. Restoring movement choices

If failing a test represents an LMC then retraining must be steered to restore this choice. The clinical application of movement retraining interventions, focusing on restoring movement choices, aim to provide the

Table 4
Test description CMCT: Kinetic Medial Rotation Test.

Kinetic Medial Rotation Test	Tests for scapula control (scapular forward tilt) and glenohumeral control (anterior translation)
Start position 	Supine with 90° humeral abduction (hand to ceiling with humerus) in plane of scapula (use to block/towel for support) – palpate coracoid and humeral head
Test movement 	Move: arm to 90° gleno-humeral joint medial rotation and return
Benchmark:	60° gleno-humeral medial rotation – arm abducted 90°
Test pass	No observable/palpable loss of scapula orientation into forward tilt or glenohumeral joint into anterior translation
Presence of loss of movement choice	Observable/palpable loss of scapula orientation into forward tilt or glenohumeral joint into anterior translation

Table 5
Test description CMCT: Single Leg Small Knee Bend.

Single Leg Small Knee Bend Test	Tests for control of hip flexion
Start position 	Stand feet hip width apart with inside borders of feet parallel, stance is upright with upper body vertical, trunk level, neutral pelvis and weight balanced over midfoot. Shift weight onto one foot and lift other foot just clear of the floor. In this single leg stance the 2nd metatarsal is aligned along neutral line (a line that is 10° lateral to the sagittal plane). No lateral deviation, tilt or rotation of the trunk or pelvis. The head, sternum and pubic symphysis should be vertically aligned above the inside edge of the stance foot with the shoulders level. The trunk is upright
Test movement 	Perform small knee bend, by flexing knee and dorsiflexing ankle, keeping heel on floor (body weight on heel not ball of foot). Line of femur ideally remains on the 10° 'neutral line' (knees out over 2nd toe. Trunk stays vertical
Benchmark:	Knee flexion to 3–8 cm past toes with trunk upright
Test pass	No observable movement of hip into flexion (trunk lean)
Presence of loss of movement choice	Observable loss of hip into flexion (trunk lean)

Table 6
Test description CMCT: The Double Knee Swing Test.

The Double Knee Swing Test	Tests for control of low back and pelvis rotation, low back and pelvis side-bend, hip flexion, lower leg lateral rotation, foot eversion
Start position 	Stand with the feet under hips (10–15 cms apart). Inside edges of the feet parallel and aligned straight ahead. Keeping heels down and trunk upright, bend the knees and lower the hips into a ¼ squat position until the knees are flexed approximately 5 cm in front of toes, with the thighs aligned out over the second toe (Small Knee Bend position). The back should be straight and vertical as if sliding down a wall
Test movement 	Swing both legs simultaneously to the left and then right to 20° range of hip rotation (E.g. as the knees swing to the (L), the (L) hip should laterally rotate to 20° away from the midline and the (R) hip should simultaneously medially rotate 20° across the midline. The pelvis should not rotate or laterally shift to follow the knees. As the knees swing side to side, allow the feet to roll and shift weight from the inside edge (pronation) to the outside edge (supination). As the knee swings out into lateral rotation, do not allow the foot to invert. Keep the 1st metatarsal head (base of the big toe) fully weight bearing on the floor. Do not allow it to unload or lift off
Benchmark:	The range of knee swing with both knees moving simultaneously should be 20° to each side
Test pass	No observable movement of low back and pelvis rotation, low back and pelvis side-bend, hip flexion, lower leg lateral rotation, foot eversion
Presence of loss of movement choice	Observable movement of low back and pelvis rotation, low back and pelvis side-bend, hip flexion, lower leg lateral rotation, foot eversion

individual with the ability to access the wealth of potential present within motor abundance; giving individuals more 'ways' to achieve movement outcomes. Retraining movement coordination strategies demands observable movement to be controlled whilst moving elsewhere. Such cognitively and biomechanically constrained patterns of coordination rarely appear during function. However, this intervention seeks to restore choice in the building blocks of coordination, required for more complex movement coordination strategies. Movement coordination strategy retraining interventions cannot be considered to be the end goal of this individual's journey but do represent a stepping stone on this path.

4.1. *Strategies to restore movement choices*

The fundamental aim of movement retraining interventions is to transition individuals towards a more robust state of movement health. This is illustrated in Fig. 3. Some considerations for restoring movement choices with cognitive movement control retraining are detailed in Table 8, and strategies and illustrations previously described (Mottram and Comerford, 2008; Mottram et al., 2019; Worsley et al., 2013).

The movement retraining intervention is informed by identifying the site, direction and threshold ® of LMC and a clinical reasoning process to match priorities to client's goals. For example, a goal may be to manage pain and local tissue stress by sharing the demands of function across a range of tissues or restore movement choices for improved performance. The process of retraining movement coordination strategies has been shown to have clinical utility at the shoulder (Worsley et al., 2013; Struyf et al., 2013) and hip and groin (Wilson et al., 2018; Mottram et al., 2019). These papers support proof of concept of this approach, however more robust evidence is required. A systematic review and

Table 7
Test description: Split Squat and Fast Feet Change.

Split Squat and Fast Feet Change	Tests for control of low back and pelvis side-bend, hip flexion, hip medial rotation, tibia lateral rotation, foot inversion
Start position 	Step out with one foot (4 foot length), feet facing forwards and arms folded across chest. Keeping the trunk upright, drop down into a lunge.
Test movement 	Rapidly switch feet in a split squat movement, control the landing. Then lift the heel of the front foot to full plantarflexion and hold this heel lift in the deep lunge for 5 s, then lower the heel and without straightening up, rapidly switch feet in a split squat movement, control the landing After the landing, again lift the heel of the front foot to full plantarflexion and hold this heel lift in the deep lunge for 5 s. Repeat the heel lift twice with each leg in the forward position
Benchmark:	Deep lunge (4 x foot length) with heel lift (5 s hold) and rapid split squat (x 4 reps)
Test pass	Minor deviations in body alignment but followed by a rapid restoration of original alignment in low back and pelvis side-bend, hip flexion, hip medial rotation, tibia lateral rotation, foot inversion
Presence of loss of movement choice	Large amplitudes of movement in any of the following sites and directions or an inability to immediately restore original body alignment; low back and pelvis side-bend, hip flexion, hip medial rotation, tibia lateral rotation, foot inversion. Oscillating in any plane constitutes a fail

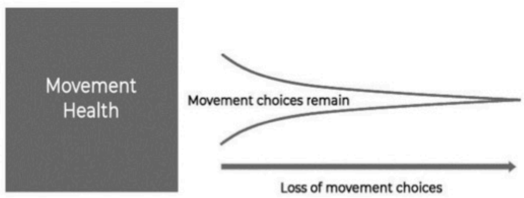

Fig. 3. This figure is a conceptualised representation of how movement choices may be lost. The aim of retraining is to restore movement choices. (Reproduced with permission of Comera Movement Science).

meta-analysis of eleven publications in 2018 explored the effectiveness of movement control exercises, on patients with non-specific low back pain and movement control impairments (Luomajoki et al., 2018). There was low to moderate quality evidence, suggesting a positive effect of movement control exercises on disability and pain severity, in the short-term and long-term, in nonspecific low back pain. Clearly, further high quality RCT's are required into the effectiveness of this approach. However, eligibility criteria must include the presence of LCMs. The present authors propose using CMCTs to identify the presence of LCMs can be used to stratify patients likely to respond to retraining. This approach empowers people to restore choice in movement (access motor abundance) and sits within the bigger clinical reasoning picture.

Table 8
Considerations for restoring loss of movement choices with cognitive movement control retraining.

Considerations for Restoring Movement Choices with Cognitive Movement Control Retraining
Restoring Loss of Movement Choices (LMC)
The person is taught to move an adjacent joint above or below in the same direction as the loss of movement choice (LMC), or same joint (in a different direction of the LMC) only as far as:
• movement is independent of the LMC
• control can be maintained at the site of the LMC
• any joint or myofascial restriction permits
Facilitation
Feedback tools can be employed to teach and facilitate the restoration of choice in coordination
• visual feedback (watch the movement)
• visualisation (including imagery)
• palpation feedback (with the person's own hands)
• kinaesthetic feedback (with adhesive tape and skin tension)
• verbal instruction and verbal correction, and motion monitoring equipment (e.g. pressure biofeedback)
• the body or limb weight may be unloaded (supported)
• proprioceptive input
• encourage normal breathing patterns
• the person should regain awareness of alignment, movement precision, muscle tension and effort, the sensation of 'easy' patterning, multi-joint motion differences
Repetition
Slow, low effort repetitions of the movement pattern are required
• practise until it feels familiar and natural
• numerous repetitions are required to elicit change in the patterns of coordination
• a general guide is to perform 20–30 or up to 2 min, of slow repetitions x 2 day (Worsley et al., 2013)
• supplying structure to this volume of work to be performed to increase engagement (Newell and Verhoeven, 2017)
• the retraining interventions should produce or provoke any symptoms
'Time under attention' (McNeill and Blandford, 2015), active, cognitive engagement with the movement task performed
• mindful movement and requires cognitive retraining
• tasks are not so easy that they fail to stimulate focused attention, nor so difficult that continuous failure undermines motivation (Kiely, 2017)
Progression
Challenging the ability to display choice in movement is essential in a progressive programme and can be facilitated by:
• reducing load facilitation (unloading)
• adding a proprioceptive challenge to the base of support
• incorporating an 'unstable' base e.g. balance boards, discs, Pilates reformer, gym balls and other small equipment
• retraining progressed into task-specific situations to meet the demands of function
• cognitive loading (cognitive loading) (Burcal et al., 2019)
• mindful movement practices e.g. Garuda, Pilates, Tai Chi, Yoga, Feldenkrais
Motor Learning
Three progressive phases of learning (Fitts and Posner, 1967)
• cognitive phase, understanding of the required action
• associative phase, practice of the programme learned in the cognitive phase
• autonomous phase, during which the performer learns to carry out the skill with little conscious effort
• cognitive input in the early stages of motor learning, and simple, single plane movement patterns can help shape the pattern
Learning transfer and retention
• restoration of the ability to display choice in the specific sites and directions considered to be most germane to the patient's presentation is fundamental to this approach; ideally, these restored movement choices augment individuals' problem -solving repertoire, remaining accessible in the presence of imposed demands
• no one approach to facilitating transfer into function is likely to prove successful for all patients (Newell and Verhoeven, 2017) a range of strategies is required
• consider the use of analogies (Andy et al., 2017) (for example, 'smiling clavicles' to aid restoration of choice associated to inability to prevent downward rotation of the scapula)
• motivation is key to transfer (Pugh and Bergin, 2006; Gokeler et al., 2019) the intervention must be strongly connected to the achievement of a change in state that possesses value to the individual
Adherence & Education
Facilitate adherence
• consideration of an agreement between patient and therapist on shared view of management plan, including initial, ongoing and maintenance programmes considering patient preferences
• behaviour goal setting – agree a contract with patient that they will do exercises to achieve desired outcome in terms of movement retraining
• explore the individuals understanding, beliefs and expectations
Education in value of restoring loss of movement choices
• gaining insight into link between LMC, presentation and goals and why it will help recurrence
• understanding how the site and direction of LMC relates to pain provocation - gaining cognitive awareness of how movement can influence pain
• develop an understanding of retraining movement strategy and why it will help symptoms and recurrence
• be mindful of the time scale, repetitions and progressions required to invoke change
• allow person to demonstrate an ability to perform the retraining movement strategy – help them learn to judge when they are controlling the LMC

5. Clinical reasoning

This paper champions 'movement' as the primary means of intervention to manage pain, limit its recurrence and enhance quality of life. Ultimately, these interventions seek to move individuals towards a sustained, robust state of movement health, by restoring movement choices. However, this process will be optimised if it fits within a person-centred approach, which considers the influence of multiple constraints on any movement coordination strategy.

A multi-dimensional, individual-centred, clinical reasoning framework is proposed based on the consideration of the numerous factors influencing movement choices including:

1. Evaluation of Movement Health, in terms of Site, Direction, Threshold ® of loss of choices in movement
2. Evaluation of syndrome, pathology, clinical signs and imaging findings
3. Consideration of pain mechanism
4. Consideration of any other individual, environmental and task constraints (Comerford and Mottram, 2012) (Fig. 4).

The interactions of these elements will drive the priorities of clinical interventions. Fig. 5 illustrates a model for consideration of assessing and restoring LMC. At the centre of this pathway is the status of an individual's movement health.

Movement health is constantly in a state of flux in response to the influence of numerous constraints. Despite the ever-changing influence of constraints, maintaining movement health across the lifespan may facilitate an individual's progress towards their highest attainable standard of health. Empowering individuals to consider the relationship between life goals, their status of movement health and a sense of how

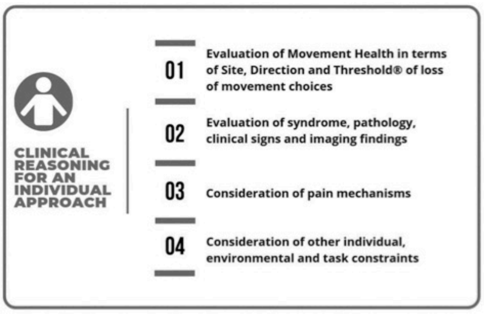

Fig. 4. A clinical reasoning framework based on four key factors influencing movement choices (Reproduced with permission of Comera Movement Science).

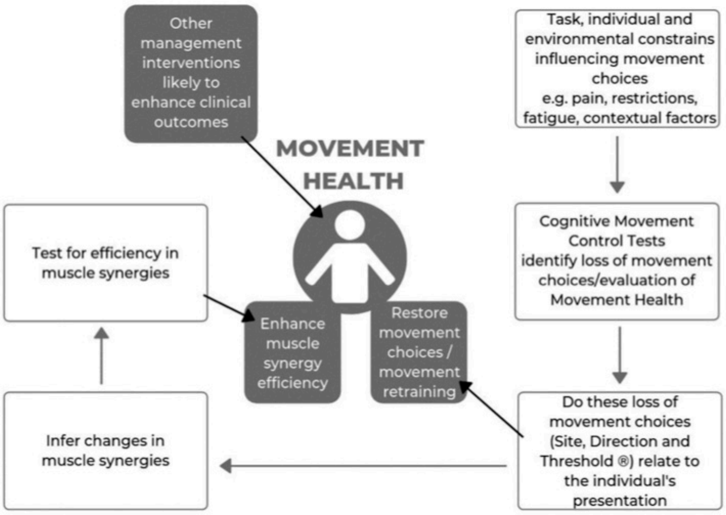

Fig. 5. The assessment and retraining of loss of movement choices within a clinical reasoning framework (Reproduced with permission of Comera Movement Science).

their efforts to improve this property can influence their life outcomes, is central to the movement health concept.

Numerous other therapeutic and educational interventions can positively influence movement choices, for example, manual therapy, soft tissue and fascial approaches, pain neuroscience education and cognitive behavioural approaches. The CMCT system can be utilised as an outcome measure to track progression (Mottram et al., 2019).

5.1. Interpreting muscle synergies

Muscle synergy characteristics have been shown to change in the presence and history of pain (Blandford et al., 2018b; Feeney et al., 2018; Liew et al., 2018). These changes are accompanied by alterations in joint coordination in the lower extremity (Kim et al., 2019). In the shoulder, Worsley et al. observed that scapular downward rotation in individuals with shoulder pain was accompanied by changes in recruitment of serratus anterior and lower trapezius (Worsley et al., 2013). The consistent patterns of movement coordination strategies employed by these individuals on arm elevation, was characterised by more downward rotation than in pain-free individuals. Following retraining these individuals appeared to employ movement coordination strategies as used by those in a more robust state of movement health. There is promising clinical support for the assessment of movement coordination strategies to infer upon relevant changes in muscle synergies. The clinical framework in Fig. 5 includes the consideration of altered muscle behaviour to support clinical decision making. Once the site and direction of LMC has been established, the associated muscle synergies can be explored in respect to movement health. This is an emerging area if interest to the researcher and clinician (Liew et al., 2018; Kim et al., 2019; Mehrabi et al., 2019).

6. Summary

The health of the movement system may be informed by the ability to display choice in movement, accessing the wealth of movement coordination strategies afforded by motor abundance. An assessment framework for evaluating patterns of movement coordination strategies is detailed with CMCTs. Restoration of movement choices identified as lost on testing are explored through cognitive movement control retraining interventions. Sitting along-side other interventions, this approach supports sustained, robust problem solving to facilitate enhanced quality of life across the lifespan.

7. Conclusion

This Masterclass sets out a perspective on how movement and its problem-solving capacity can be assessed and modified in the clinical setting. For clinicians wishing to adopt a movement-based approach, the identification of LMC may contribute to the clinical reasoning process. Proof of concept of this perspective has been outlined, and clearly further research is needed to improve the quality of evidence to support this approach.

Ethical approval

Not applicable.

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Declaration of competing interest

Sarah Mottram and Lincoln Blandford are employees of Comera Movement Science Ltd, which educates and trains sports, health and fitness professionals to better understand, reduce and manage musculoskeletal injury and pain that can impair movement and compromise performance in their patients, players and clients.

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Case Report

Retraining in a Female Elite Rower with Persistent Symptoms Post-Arthroscopy for Femoroacetabular Impingement Syndrome: A Proof-of-Concept Case Report

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Abstract: Athletes with femoroacetabular impingement syndrome (FAIS) managed arthroscopically do not always return to sport. Inability to control back/pelvis, hip and lower limb movements may contribute to the onset and recurrence of symptoms. Our hypothesis is that results from a battery of cognitive movement control tests can inform a cognitive movement control (neuromuscular) retraining programme for improving the clinical presentation and quality of life in an athlete with FAIS. This case report presents a female elite rower with persistent left-sided anterior hip pain, four years post-arthroscopic surgery for FAIS, whose symptoms failed to respond to conventional physical therapy. Hip and groin outcome score (HAGOS), passive and active hip flexion range of motion (ROM) workload (time training on water), hip and pelvic kinematics (3-D motion analysis) and electromyography during a seated hip flexion movement control test, and a movement control test battery to identify movement control impairments (The Foundation Matrix), were assessed pre-intervention (week 0) and immediately post-intervention (week 16). Impaired movement control was targeted in a tailored 16-week cognitive movement control retraining exercise program. All measures improved: HAGOS (all 6 sub-scales); symptoms (61/100 pre-training to 96/100 post-training); physical activities participation (13/100 to 75/100); and active hip flexion ROM increased (78 to 116 and 98 to 118 degrees, respectively); workload increased from 4 to 18 h/week; and movement control impairment reduced (25/50 to 9/50). Pelvic motion on kinematic analysis were altered, and delayed activation onset of tensor fascia latae and rectus femoris muscles reduced. This proof-of-concept case report supports the hypothesis that cognitive movement control tests can inform a targeted cognitive movement control retraining program to improve symptoms, function and quality of life, in an elite rower with persistent hip pain. This training offers an alternative approach to conventional physical therapy, which has failed to restore function in FAIS, and the present study illustrates how specific cognitive movement control assessment can direct individual training programmes.

Keywords: femoroacetabular impingement syndrome; movement retraining; kinematics; electromyography; movement control impairments.

1. Introduction

Femoroacetabular impingement syndrome (FAIS) is a motion-related condition of the hip with a presentation of symptoms, clinical signs and imaging findings and represents symptomatic premature contact between the proximal femur and the acetabulum [1]. It is associated with labral tears [2] and osteoarthritis [3]. This paper describes the conservative management of an elite rower with persistent FAIS and a history of labral pathology, specifically involving assessment to identify movement control impairments (MCIs), and so an individualised cognitive movement (neuromuscular) control retraining programme could be devised and tested.

Effective transfer of power through the rowing sequence is essential for effective technique and ultimately optimal performance [4]. Buckeridge [4] explored biomechanical factors influencing foot force production and asymmetries at the foot stretchers in rowers and how this impacted the efficiency of transfer to the handles/oars. Results illustrated that: (1) hip kinematics, specifically greater degrees of hip flexion, influenced greater foot force output; (2) horizontal foot force was influenced by knee and lumbo-pelvic kinematics, i.e., less movement and a more stable lumbo-pelvic region was associated with a more rapid extension of the knee and better force transmission; and (3) foot force asymmetries were related to lumbo-pelvic kinematic and pelvic rotation. These findings indicate that the range of hip flexion and control of lumbo-pelvic movements are important for effective and efficient rowing technique and performance.

Changes in movement patterns and biomechanics have been reported in people with FAIS [5,6]. Diamond [5] found that individuals with FAIS demonstrated greater hip and lumbo-pelvic asymmetries, including lateral trunk lean, pelvic rise and hip abduction, in a step-up task compared to unaffected individuals. King's [6] systematic review on lower limb biomechanics in FAIS highlighted individuals with FAIS had less hip extension, total hip range in the sagittal plane and peak hip internal rotation during walking and did not squat as deeply, although hip flexion range in the squat was same as controls. These findings illustrate hip biomechanical impairments in FAIS and the need for individualized assessment to gain an understanding of a person's movement patterns and pain presentation

Pain in FAIS is typically motion-related or position-related [1]. The mechanism of repetitive hip flexion required for rowing may predispose to FAIS. In rowing, movement of the knee towards the chest is a combination of hip flexion and posterior pelvic tilt. Ross et al. [7] explored the effect of dynamic changes in pelvic tilt on functional acetabular orientation and occurrence of femoroacetabular impingement. In particular, they observed a dynamic anterior pelvic tilt resulted in the earlier occurrence of impingement in the arc of motion, whereas a dynamic posterior pelvic tilt resulted in a later occurrence of impingement.

Van Houcke [8] reported that posterior pelvic rotation during active (but not passive) hip flexion (in supine) was increased in people with FAIS, and that active and passive hip flexion range of movement (ROM) were significantly decreased. Their findings suggest an active mechanism for the altered pelvic-femoral rhythm as an adaptive or protective mechanism to maintain function of the knee moving towards the chest while minimizing the anterior impingement. This posterior pelvic rotation serves to rotate the anterior acetabulum away from the femoral neck, thereby allowing a greater knee to chest ROM, which is a critical function for rowing. As a link is now emerging between dynamic changes in pelvic rotation and FAIS, biomechanical observations of pelvic tilt were included in the present study.

Since altered movement can be associated with pain, the function of hip musculature is important to consider in the management of FAIS. Deficits of hip muscles strength including hip flexors are observed in people with FAIS [9]. A recent systematic review explored the current evidence investigating muscle size and composition in articular hip pathology [10]. Although some low-quality evidence of smaller size in specific hip muscles of the symptomatic limb in unilateral osteoarthritis (OA) was identified, no difference was seen in the cross-sectional area in pincer FAIS and acetabular labral pathology using MRI. Meta-analysis was only possible for hip OA, but the review highlighted the variability in hip muscle size between those with and without hip pathology, indicating the need for further research to explore muscle changes in individuals with hip pain including FAIS. In addition, Mendis [11] demonstrated reduced hip muscle strength in patients with labral pathology but no differences were observed in hip flexor recruitment patterns. Although not directly assessing hip muscle size or strength, the present study examined behaviour of the hip muscles during functional tests. Few studies have investigated lower limb electromyography (EMG) in FAI and no EMG studies were found on rowers. Some preliminary research has identified changes in hip synergy recruitment in people with FAIS [12]. It is well established that musculoskeletal pain alters the structure of variability in muscle control. This is supported by a recent review highlighting consistent evidence that muscle synergies differ between asymptomatic individuals and those with musculoskeletal pain [13].

Conservative treatment has been promoted for the initial nonoperative treatment for FAIS [14]. The authors reported that available literature with experimental data is limited but suggested that physical therapy and activity modification provide some benefit to people with FAIS. However, the authors emphasised that nonoperative strategies, particularly physical therapy, need to be evaluated more extensively and rigorously to determine the true clinical effectiveness. Two recent randomised controlled trials (RCTs) demonstrated that hip arthroscopy showed superior outcomes with arthroscopic hip surgery compared to personalised hip therapy (physical therapy) [15,16]. A single-centre RCT reported no difference between the groups [17].

Two of these RCTs reported that the personalised hip therapy groups demonstrated some improvement in hip-related quality of life score as measured by the international hip outcome tool (iHOT-33) [15,17]. However, post-intervention, participants still demonstrated scores of less than 50 points out of 100 for the iHOT-33, indicating impairment persisted. Reference values for the iHOT-33 for healthy hips were not reported in these papers. Mansell [17] did not find differences between arthroscopic surgery and physiotherapy at any time point up to a two-year follow-up, although there was a 70% crossover from physiotherapy to arthroscopic surgery in this small trial, highlighting limitations of the study [17]. Palmer reported a clinically important improvement (at least 9 points) in the hip outcome activities of daily living subscale (HOS ADL) in 50% of the physical therapy group compared to 70% in the arthroscopy group [16]. The patient acceptable symptomatic state (PASS), defined as HOS ADL greater than 87 points, was achieved in 48% of the arthroscopic group and 19% of the physical therapy group. Palmer also reported a 10-point mean difference on the HOS ADL between groups, which is greater than the MCID of 9 points, in favour of arthroscopic surgery [16]. Griffen reported the mean difference of iHOT-33 scores was 6.8% in favour of hip arthroscopy [15]. Physical therapy sessions varied from 6–12 sessions over 12–24 weeks in the three studies. Considering the uncertainty in the effectiveness and appropriateness of the personalised hip therapy interventions (see below), caution must be applied to the generalizability of these programmes used. Personalised hip therapy was more cost-effective than arthroscopy in the short-term (12 months) and five out of 171 participants (2.9%) reported a serious adverse effect of surgery [15]. In summary, although both interventions produced positive outcomes, surgery would appear to be a superior option but impairments persisted for both.

Regarding the appropriateness of the physical therapy interventions used in the above trials, all three included exercises [15–18] but targeted cognitive movement control training of individual MCIs was not undertaken. This training approach reported in the present paper is increasingly recognised as being more effective than conventional physical therapy [19,20], although it is not always applied using the specific cognitive movement control assessment used in the present study. These approaches have yet to reach the wider clinical audience and the present case study will help to highlight this gap.

A recent editorial challenged current best practice for non-surgical management of FAIS and asked the pertinent question: "are we providing high-quality, outcome driven, exercise therapy programs to these patients?" [21]. Specifically, the editorial by Kemp questioned whether the non-surgical treatment programmes included the type, dose and progression of exercises needed to generate a meaningful change in strength and function [21]. This includes questioning what constitutes (1) contemporary "optimal non-surgical care" for patients with FAIS, (2) contemporary "optimal post-surgical rehabilitation" and (3) an effective, contemporary return to sport programmes for patients with FAI syndrome [21].

A recent paper considering exercise in the management of spinal pain highlights that the outcome of exercise interventions can be optimised when tailored to address the neuromuscular impairments of each individual [22]. The authors emphasised that because of the heterogeneity of individual features in the presentation, including variability of motor adaptations, there can be no recipe approaches. A better outcome will be achieved if each person is regarded as an individual, and the retraining programmes are designed and tailored to each individual. The basis of this retraining is on a sound assessment.

Movement is complex and influenced by many components. An adapted model of the dynamic systems theory has been presented by Dingenen et al. [23]. The model proposes that an individual's movement pattern emerges out of interaction between three domains. These domains include factors related to the person (e.g., age, hip pathologies), the task being performed (e.g., walking, stages in rowing stroke), and the environment or context in which it is performed (e.g., race conditions, training). Interventions including exercise and movement retraining can focus on any of these domains in order to produce a clinical outcome. However, a focus upon the movement pattern emerging from these interactions is of interest to both clinicians and researchers [23]. The influence of movement coordination patterns and muscle synergy recruitment on pain, function and biomechanics are the focus of the present paper.

The concept of identifying and retraining MCIs is underpinned by human movement science (biomechanical and neurophysiological) [23–25]. An ability to consciously demonstrate variation in the co-ordination strategies to achieve a movement can be considered to illustrate choice in movement [23,26]. Cognitive movement control assessment can be used to evaluate MCIs by questioning an individual's ability to cognitively coordinate movement at a specific joint or region (site) in a particular plane of movement (direction), under low- and high-threshold loading, often during multi-joint tests within functionally orientated tasks [23,27]. The identification of specific MCIs can be used to inform the content of the retraining program [23–25].

Our hypothesis is that results from a battery of cognitive movement control tests identifying MCIs can direct a cognitive movement control retraining programme for improving the clinical presentation and quality of life of an athlete with FAIS. In addition, the authors hypothesise that the training intervention will influence pelvic kinematics with less dynamic pelvic movement on hip flexion, accompanied by changes in EMG activity, in terms of delayed onset. Rejection of the null hypothesis would call for the need to review current practice for personalised hip therapy. The present case report describes the movement control assessment and retraining of a female elite rower, who had failed to respond to hip arthroscopy and conventional physical therapy. The aim was to identify MCIs and examine the effect of a tailored cognitive movement control retraining program, designed to correct MCIs, on clinical presentation, quality of life and associated changes in biomechanical and neurophysiological indicators of underlying mechanisms of movement control.

2. Case Description and Methods

2.1. Participant Details

A 26-year-old female elite rower (height 182 cm, weight 68 kg) presented with left anterior hip pain. She began rowing aged nine years and from the age of 15, trained up to 28 h a week. She complained of left anterior hip pain for 12 years and FAI (pincer) was diagnosed via X-ray and confirmed using magnetic resonance imaging. Arthroscopic surgery, performed four years prior to the present case study (modification of acetabular and removal of calcified hip labrum), did not alleviate symptoms. Her main complaint on presentation was persistent anterior hip/groin pain on rowing and other activities requiring lifting the knee towards the chest, e.g., cycling, climbing stairs, sitting in a low chair. Symptoms limited her training time and intensity, and participation in competitive rowing. Previous physiotherapy included treatment to the lumbar spine, soft tissue therapy and stretches to the low back/pelvis and hip restrictions.

The study was approved by the Faculty of Health Sciences, University of Southampton Ethics Committee (Ethics ID 6732, approved 3 July 2013) for case studies of hip and groin pain. The participant provided written informed consent.

2.2. Outcome Measures

Assessments were performed pre-intervention (0 weeks) and 16 weeks post-intervention. Both clinical and laboratory-based measures were used. Hip and groin outcome score (HAGOS) [28,29], a patient reported outcome measure recommended for the assessment of young-aged to middle-aged physically active individuals with hip and groin pain was the main outcome measure. The HAGOS consists of six separate subscales assessing pain, symptoms, physical activities and hip and/or groin-related quality of life (QOL) [29]. The test–retest reliability of the questionnaire was shown by the group that devised the HAGOS [29] to be substantial, with intraclass correlation coefficients (ICC) ranging from 0.82–0.91 for the six subscales. Construct validity and responsiveness were confirmed with statistically significant correlation coefficients 0.37–0.73 ($p < 0.01$) for construct validity, and 0.56–0.69 ($p < 0.01$) for responsiveness [29]. The HAGOS, therefore, has adequate psychometric properties for the assessment of symptoms, activity limitations, participation restrictions and QOL in physically active, young-to-middle-aged patients with longstanding hip and/groin pain [29]. Active and passive hip flexion were measured in supine using a plurimeter placed on the distal thigh. The participant was asked to bring one knee towards their chest as far as possible. The plurimeter has a rotating dial, which allows easy reading of the angle of movement to the nearest 2° [30]. It has been shown that the measurement of hip flexion ROM are repeatable between practitioners (ICC 0.87) using a plurimeter [30]. For passive assessment, the assessor moved the lower limb into hip flexion until pelvic movement occurred. Any pain provocation was noted.

2.2.1. Identifying Movement Impairments: The Foundation Matrix Test Battery

MCIs were identified using The Foundation Matrix, part of The Performance Matrix movement analysis system, Movement Performance Solutions Ltd., which is a battery of 10 multi-joint functionally relevant cognitive movement control tests that identifies MCIs. Failing a cognitive movement control test demonstrates a loss of choice about how a movement is achieved [23]. This test battery reveals the movement "choices" lost during postural and non-fatiguing tasks (low threshold recruitment) and in fatiguing load and speed tasks (high threshold recruitment). As these different loading/intensity environments are influenced by different physiological mechanisms, testing is suggested to inform about loss of movement choices and the presence of low movement coordinative variability across a spectrum of tasks. The ability to pass a battery of cognitive movement control tests in all planes of movement illustrates a desirable wealth of choice in movement options (high movement coordinative variability) [23]. The tests have been described by Mischiati [27] and Test 1: Double knee swing was described, by Dingenen and McNeill [23,31]. The inter- and intra-rater reliability of this tool has been found to be acceptable [27]. The system reports the site (e.g., hip), direction (e.g., flexion) and threshold (low or high) of MCIs [23,27]. Reports produced by an inbuilt algorithm in the online system present MCIs that appear as areas of high risk, subsequently guiding clinical reasoning and development of a prioritisation plan for retraining. A movement control impairment score is given out of 50 (lower score indicates fewer MCIs). The Foundation Matrix is suggested to have clinical utility for the assessment of MCIs [27] and the value of assessing movement within the world of movement health, injury prevention and rehabilitation has been presented by Dingenen [23]. The test battery is employed by therapists in clinical settings for the assessment of MCIs.

2.2.2. Retraining Programme

The retraining programme consisted of four therapist-led training weeks and a bespoke home exercise programme. At weeks 1, 2, 10 and 16, the athlete attended for five daily sessions (2 h a day contact time).

The Foundation Matrix report was used to develop the retraining programme (see Section 3: Results), focusing on high-risk areas and progressing to low risk areas. Priorities included retraining MCIs of the low back and pelvis, hip and foot. In this case study, six priorities for retraining were identified, reflecting the relevance of the MCIs to the provoking activity, symptoms and goals of the individual (see Supplementary File).

Exercises included low threshold motor control recruitment retraining twice a day and high threshold strength and speed retraining up to four times per week. Strategies were directed at retraining the MCIs with either direction control retraining (co-ordination patterns) or muscle-specific retraining (muscle synergy recruitment) [24,25]. This cognitive stage represents an initial rehabilitation phase in a progression back to functional tasks. The retraining programme is detailed in the Supplementary File and involved cognitive strategies to influence both motor learning and elicit subsequent change to movement patterns and did not include manoeuvres that formed the tests of movement control.

Three progressive phases of learning a new skill were proposed by Fitts and Posner in 1967 [32]: cognitive phase, understanding of the required action; associative phase, practice of the programme learned in the cognitive phase; and autonomous phase, during which the performer learns to carry out the skill with little conscious effort. Bernstein [33], also in 1967, proposed that freezing during motor learning (restricting joint ranges of motion and tightly coupling the motion of different joints) is prevalent mainly during the early stages of motor learning and gradually decreases as learning progresses. More recently, van Ginneken's [34] experimental paper suggests that conscious control is associated with the freezing of mechanical degrees of freedom during motor learning. This highlights the importance of cognitive input in the early stages of motor learning, and simple, single plane movement patterns. These strategies were implemented in the athlete's early retraining programme.

2.2.3. Identifying Movement Control Impairments: Movement Control Test with Motion Analysis during Seated Hip Flexion

This test examined the ability to actively control movements of the pelvis during hip flexion. The participant was seated on a couch (90° hip and knee flexion, feet unsupported, arms folded across chest) and instructed to lift one knee towards the chest, until the femur was 20° above horizontal (approximately 110° hip flexion), whilst keeping the low back/pelvic region still (Figure 1). The task was repeated three times per side. Kinematics of the pelvis and lower limbs were obtained using a Vicon MX 3-dimensional motion capture system with 12 T-series cameras operated at 100 Hz (Vicon Motion Systems, Oxford, U.K.). Retro-reflective markers were attached bilaterally according to the Vicon plug-in gait model [35], on the anterior super iliac spine (ASIS), mid-thigh, lateral femoral condyle, lateral tibia, lateral malleolus, calcaneus and dorsal aspect of the head of the first metatarsal. Additional markers were attached to the medial femoral epicondyle and medial malleolus during a static standing trial. An Aurion "Zerwoire" EMG system was used to obtain electrical activity of tensor fascia latae (TFL) and rectus femoris (RF) muscles. Electrodes were placed bilaterally following SENIAM (Surface ElectroMyoGraphy for the Non- Invasive Assessment of Muscles) guidelines [36]. EMG data were recorded at 1000 Hz via the motion capture system to allow for time synchronisation with kinematic data.

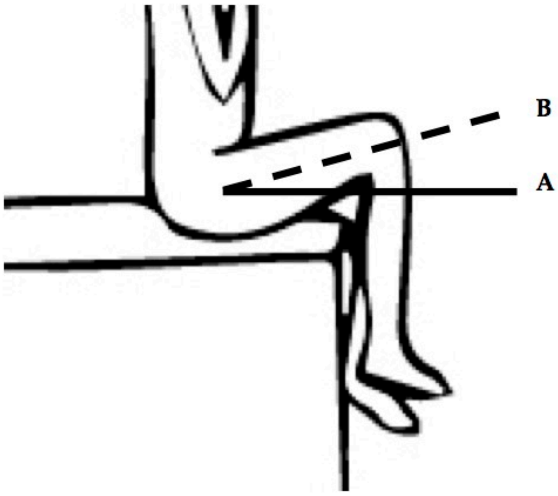

Figure 1. Seated hip flexion control test (end position): Line A illustrates the start position (90° hip and knee flexion) and Line B illustrates the end position (110° hip flexion).

Kinematic and EMG post-processing and data reduction: Kinematics of the pelvis and femur were determined using a modified version of the Vicon plug-in gait model and Vicon Bodybuilder modelling software (Vicon, London, UK). This utilized the medial femoral epicondyle and medial malleolus markers, captured during the static standing trial to ensure correct alignment of the femur flexion axes. Post-processing of kinematic and EMG data was undertaken in Matlab 8.1 (The MathWorks Inc, Natick, MA, USA). Kinematic data were filtered using a low-pass fourth order zero-lag Butterworth filter at 10 Hz and cropped to the start and end of the seated hip flexion task (start defined as first notable increase in knee lift and hip flexion from static sitting, and end as the point where hip extension ceased following lowering of the leg onto the couch) through visual inspection of the kinematic waveform. Data were interpolated to 101 data points between the start and end of the task to time-normalize the data and allow averaging across the three repetitions. Hip flexion range of movement was defined as the maximum amount of hip flexion minus the start angle of the hip. EMG data were band-pass filtered using a band-pass fourth order zero-lag Butterworth filter between 10 Hz and 500 Hz, then rectified. Onset and termination of muscle activity was determined using the on/off methodology using visual interpretation of the filtered rectified EMG signal [37] and the humeral angle where this occurred was noted. The time of muscle onset was subtracted from the time at which hip flexion commenced. A negative value indicated muscle activation commenced before initiation of hip flexion. Onset times were established for each trial then averaged across the three trials for each side, pre- and post-intervention.

3. Results

Following the 16-week cognitive movement control retraining programme, there were improvements in symptoms, function, MCIs, activity restrictions and participation, and changes in biomechanical measures and reduction in muscle onset times.

3.1. Clinical Assessment and Movement Control Assessment

Scores for all 6 sub-scales of HAGOS increased: e.g., symptoms improved 35 points and participation in physical activities improved 62 points (Table 1).

Table 1. HAGOS scores pre- and post-intervention (all scores out of 100).

Category	Pre-Intervention	Post-Intervention
Pain	53	93
Symptoms	61	96
Physical function, daily living	65	100
Function, sports and recreational activities	56	100
Participation in physical activities	13	75
Quality of life	32	85

The results from The Foundation Matrix test battery reporting the MCIs at the initial evaluation are listed in Appendix A Table A1. The report detailing the MCIs at post intervention (week 16) are detailed in Appendix B Table A2.

Passive left hip flexion increased from 78 degrees (reproduced hip pain) to 116 degrees (pain free). Active hip flexion increased from 98 degrees (reproduced hip pain) to 118 degrees (pain free).

3.2. Kinematic Findings During Seated Hip Flexion Control Test

Pre-intervention, kinematic data revealed the left side of the pelvis tilted posteriorly by 11.0°, rotated upwardly 5.2° (lumbo-pelvic hitch on left), and rotated externally 14.4° (anti-clockwise rotation). Post-intervention, the pelvis was in a greater position of posterior tilt at the start of the task compared to pre-intervention (Figure 2). There was less posterior tilt (6.5°), upward rotation (3.2°) and external rotation (10.51°) during the task compared to pre-intervention. Range of active left hip flexion was similar pre- (35.3°) and post-intervention (33.1°). Table 2 details the root mean squared error (RMS error) between the three repeated trials during the seated hip flexion task pre- and post-intervention. RMS errors are small relative to the differences observed pre- to post-intervention. RMS errors are small relative to the differences observed pre- to post-intervention.

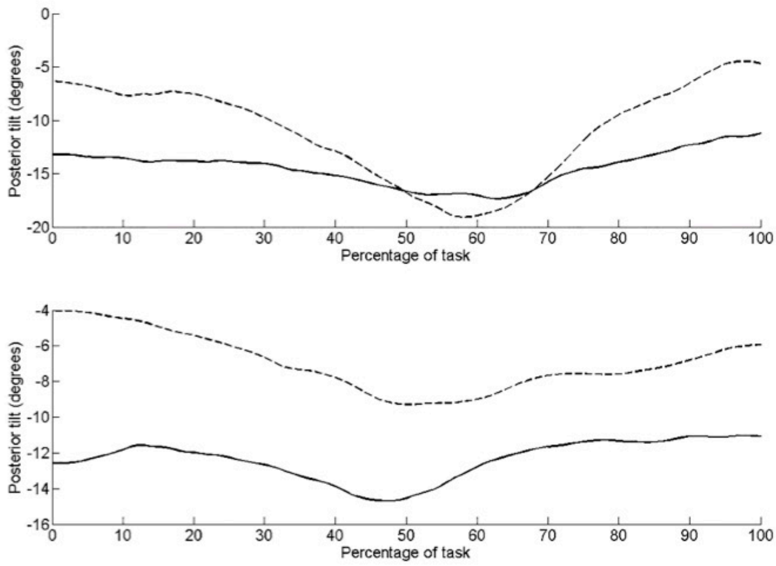

Figure 2. Posterior tilt of the pelvis during the seated hip flexion task for the left side (upper graph) and right side (lower graph). Dashed line represents pre-intervention, solid line represents post-intervention.

Table 2. Average root mean squared error (RMS error) between the three repeated trials during the seated hip flexion task for pre- and post-intervention.

Pre-intervention (left)	Pelvic tilt	1.74
	Pelvic lat tilt	0.87
	Hip flexion	2.65
	Hip internal rotation	1.66
Post-intervention (left)	Pelvic tilt	1.57
	Pelvic lat tilt	1.40
	Hip flexion	1.49
	Hip internal rotation	1.67
Pre-intervention (right)	Pelvic tilt	1.43
	Pelvic lat tilt	0.71
	Hip flexion	2.94
	Hip internal rotation	1.01
Post-intervention (right)	Pelvic tilt	0.95
	Pelvic lat tilt	0.87
	Hip flexion	3.64
	Hip internal rotation	1.06

On the right side, there was less posterior tilt (5.1°), upward rotation (0.6°) (lumbo-pelvic hitch on the right) and external rotation (10.6°) (clockwise rotation) compared to the left side pre-intervention. Post-intervention, posterior tilt and external rotation reduced to 2.8° (Figure 1) and 5.1° (Figure 3), respectively. Upward pelvic rotation was similar (0.7°) to that pre-intervention (Figure 4). The amount of hip flexion on the right side was similar pre-intervention (32.3°) and post-intervention (34.6°; Figure 5).

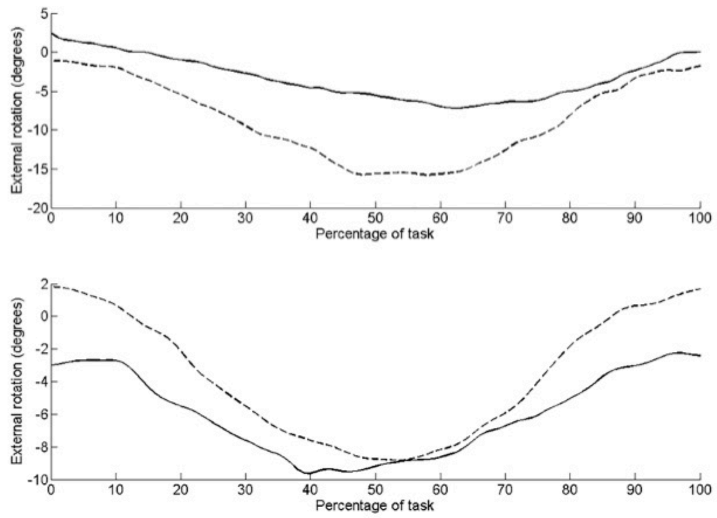

Figure 3. Pelvic upward rotation during the seated hip flexion task for the left side (upper graph) and right side (lower graph). Dashed line represents pre-intervention, solid line represents post-intervention.

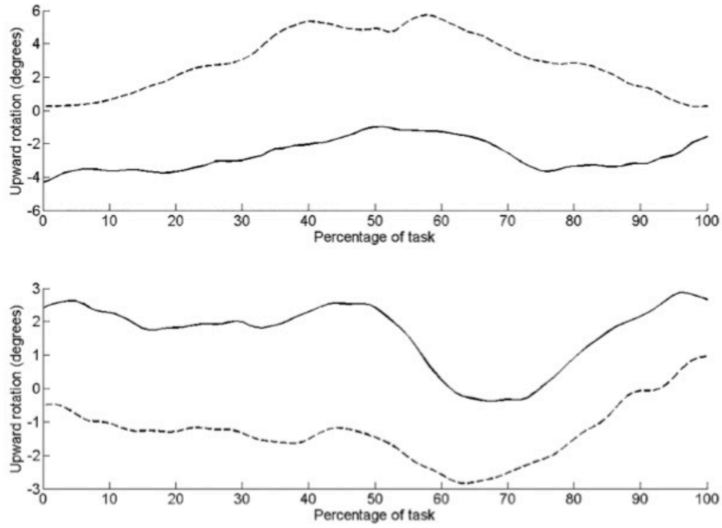

Figure 4. Hip flexion during the seated hip flexion task for the left side (upper graph) and right side (lower graph). Dashed line represents pre-intervention, solid line represents post-intervention.

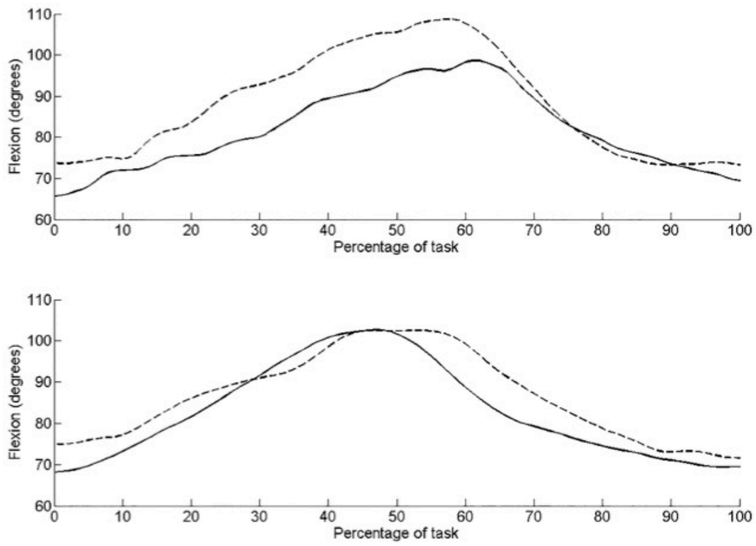

Figure 5. External rotation during the seated hip flexion task for the left side (upper graph) and right side (lower graph). Dashed line represents pre-intervention, solid line represents post-intervention.

3.3. Muscle Activation Onset

Muscle activation timing was delayed in relation to hip flexion pre-intervention and became faster post-intervention, either with a much smaller interval after hip flexion or muscle onset occurred prior to hip flexion. Specifically, pre-intervention, EMG onset of the left TFL and RF occurred 900 milliseconds (ms) and 1300 ms after the start of hip flexion. Post-intervention, onset reduced to 80 ms for RF (Figure 6) and TFL onset occurred 80 ms before hip flexion. On the right side pre-intervention, onset was delayed by 280 ms and 480 ms after the start of hip flexion for TFL and RF respectively. Post-intervention, onset of both TFL and RF muscles occurred 350 ms and 560 ms prior to hip flexion (Figure 6). Figure 7 illustrates the change in EMG onset timing pre- to post-intervention of the left TFL.

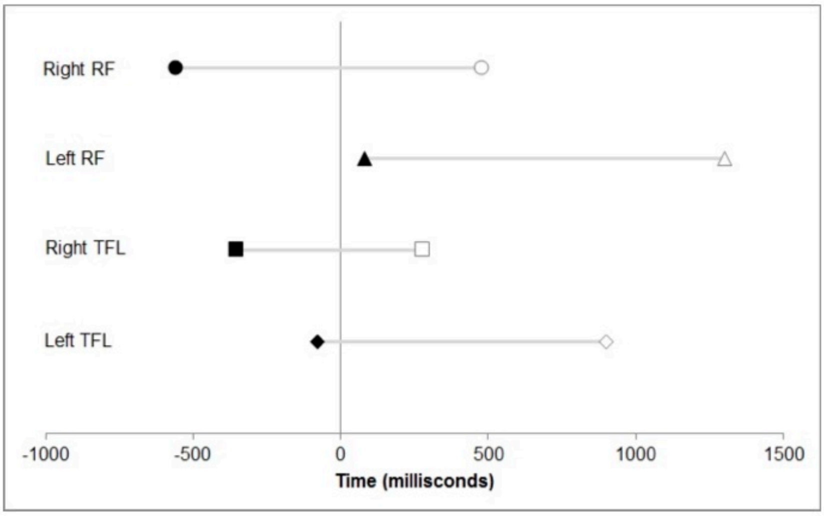

Figure 6. Onset timing of electromyographic (EMG) activity for the tensor fascia latae (TFL) and rectus femoris (RF) muscles pre-intervention (white symbols) and post-intervention (black symbols). Timing (milliseconds) is expressed relative to the initiation of hip flexion (time zero).

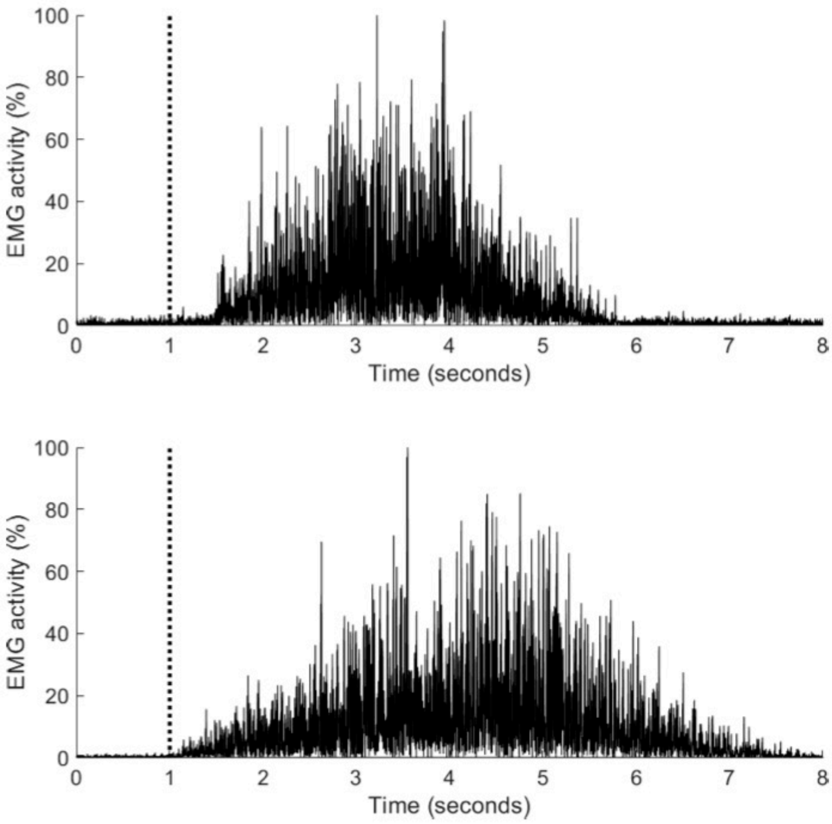

Figure 7. Onset timing of the left tensor fasciae latae muscle during the seated hip flexion task pre-intervention (upper graph) and post-intervention (lower graph). The beginning of the hip flexion (task onset) is denoted by the dotted bold line. The amplitude of the electromyographic signal was normalised to the maximum activity observed during the task.

4. Discussion

The novelty of this study is the identification of MCIs in an elite rower with persistent hip pain in order to inform a bespoke retraining programme. Proof-of-concept of the effect of a cognitive movement control retraining programme, based on assessment of MCIs has been provided by this single case study. Assessment using The Foundation Matrix test battery identified MCIs and informed the design of the movement control retraining intervention. Following the movement assessment, a 16-week cognitive movement control retraining programme was implemented targeting specific MCIs. An improvement in outcomes was noted: symptoms, activity limitations, participation restrictions and quality of life, as well as a change in biomechanical and neurophysiological function.

The HAGOS patient-reported outcome tool was used as it measures sports and activity related hip and groin function. The minimal important change (MIC) for the HAGOS subscales are pain 9.1, symptoms 8.4, activities of daily living 11.2, sport and recreational activities 9.9, participation in physical activity 12.1 and quality of life 8.0. The MICs were achieved for each subscale post intervention [38]. Thorborg [38] has reported the 95% reference value intervals, based on 158 individuals with healthy hips 99 females (mean age 39 years; range, 16-66 years) and 59 males (mean age 39 years; range, 17–57 years) for HAGOS, pain 90–100, symptoms 78.57–100, activities of daily living 94.75–100, sport and recreational activities 87.5–100, participation in physical activity 75.0–100 and quality of life 85.0–100. Each subscale in this study met these reference intervals post intervention. The 95% reference ranges for hip and groin injury-free soccer players, with no pain in the previous or present season (301 males, mean age 23.6 years, SD 4.4), have been reported as pain: 80.1–100, symptoms: 64.3–100, activities of daily living: 80.3–100, sport and recreational activities: 71.9–100, participation in physical activity: 75–100 and quality of living: 75–100 [39]. Again, each subscale met these reference intervals post intervention. These results illustrate not only achievement of MICs for the HAGOS, but reached the 95% reference value intervals within two populations with healthy hips.

From The Foundation Matrix report (Supplementary File), six priorities for movement retraining were selected from the high priority list (Table 2, Supplementary File) and included retraining of co-ordination patterns and muscle synergy recruitment. Although cognitive motor control retraining focused on the hip and low back/pelvis, the program also included the foot and shoulder girdle as movement control at these joints is also required in rowing. Control at all segments of the kinetic chain were targeted in the progression of rehabilitation.

Movement of the knee towards the chest is critical in rowing, combining hip flexion and pelvic tilt. From the outset, movement control retraining focused on control of pelvic movements and encouraging hip flexion. Training included: (1) drills to produce posterior pelvic tilt and control anterior pelvic tilt; and (2) hip flexion on a stable pelvis, encouraging hip flexion with deep hip flexor iliacus without dominance of superficial hip flexors RF and ITB.

This single case study adds to the growing body of evidence for movement control retraining [40,41]. Furthermore, the case study illustrates how movement assessment guided the retraining intervention. Neuromuscular training (involving motor control exercises) is effective for preventing risk of injury and improving performance indicators [42,43]. Although sport performance was not examined in the present case study, the cognitive movement control retraining programme enabled the participant to resume full training for competitive rowing.

The results of the present kinematic analysis post-intervention demonstrated more posterior tilt at the start of the seated hip flexion test, suggesting a change in resting posture. Post-intervention, the resting position became more similar to the asymptomatic right side. This change in postural position may have contributed to an unloading of the anterior hip tissues. This observation is supported by observations from radiographic parameters of acetabular morphologic characteristics concluding dynamic anterior pelvic tilt that is predicted to result in the earlier occurrence of FAI in the arc of motion, whereas dynamic posterior pelvic tilt results in later occurrence of FAI [7]. Ross et al. concluded dynamic changes in pelvic tilt significantly influence the functional orientation of the acetabulum. The present paper is one of the first to explore the effect of dynamic pelvic tilt and muscular control of the pelvis on anterior hip pain.

Pre-intervention, the left side had a larger excursion of posterior tilt (11.0°) during the seated hip flexion test on kinematic analysis than post-intervention, i.e., there was less excursion of the pelvis into posterior tilt (6.5°). The control of pelvic movement improved post-intervention, as indicated by less of a need for compensatory pelvic movement (less posterior tilt, side bend and rotation). Active hip flexion improved suggesting the deep hip flexor muscles were able to contribute to this movement. The overall range of seated hip flexion did not change. However, as there was improved control of the compensatory pelvic movements, we propose there was improved segmental hip flexion, i.e., more movement occurred at the hip and less at the pelvis (Figure 2). These results indicate a dynamic change in pelvic tilt during a functional movement. It is proposed that improved muscular control of the pelvis resulted in these changes in pelvic tilt. The large excursion of posterior tilt seen pre-intervention, between 40–70% of the task, is consistent with the 80–90° hip flexion where Beck [44] demonstrated impingement occurs.

Van Houcke [8] questioned whether, for some high-end sports, a rehabilitation program involving increasing posterior rotation should be employed. This posterior pelvic rotation serves to rotate the anterior acetabulum away from the femoral neck, thereby allowing a greater knee to chest range of movement, which is a critical function for rowing. Interestingly in the present study, it was noted pre-intervention that the pelvis on the left was in greater anterior tilt, suggesting a greater risk of impingement and an associated larger compensatory posterior tilt. Post-intervention, there was a change in the start position, a position of more posterior tilt. This suggests less of a need for compensatory movement; indeed, there was less movement into posterior tilt from the start position. These results from the kinematic data during the seated hip flexion control test support our hypothesis that pre-intervention, a greater excursion of pelvic movement was observed.

The onset of EMG activity has been linked with functional improvements and the present findings warrant more detailed investigation of muscle recruitment timings in people with hip pain. The present findings are consistent with those found after movement control retraining in people with shoulder pain and impingement, where improvements in EMG onset timing, scapulohumeral kinematics and function were found [41]. The present study explored the superficial hip flexors, TFL and RF, as surface EMG was used, so further studies on psoas and ilacus will require fine wire instrumentation. These results from the EMG data during the seated hip flexion control test support our hypothesis that the movement retraining intervention will alter EMG of the hip muscles.

The U.K. FASHIoN randomised controlled trial [15] and Palmer [16] both demonstrated that hip arthroscopy showed superior outcomes with arthroscopic hip surgery compared to personalised hip therapy [14]. The personalised hip therapy included exercise and activity modification but specific assessment and motor control retraining of individual MCI was not undertaken [21]. There is growing evidence in individuals with spinal pain of variations of neuromuscular adaptation [22]. This supports the need for tailoring interventions to the individual and is a growing area of research [45].

This case study illustrates how assessment of an athlete's MCIs can direct bespoke intervention. Although the assessment system is supported by an online software system, the clinical utility of the tool is advantageous due to the fact it does not burden the therapist with the need for specialised equipment. It is a clinically applicable tool used to assess MCIs. This assessment measure is a reliable outcome tool [27]. In addition, its clinical utility is to measure changes in MCIs over time following retraining interventions. The concept of cognitive movement control training does not require this particular software and other non-commercial tools can be used for assessment to inform training [41,45]. Cognitive movement control retraining (restoring movement options) has been shown to be effective in changing outcomes including kinematics [41,45]. The present paper supports our hypothesis that retraining of MCIs, identified with a structured testing procedure, can improve outcomes. Findings of the present study highlight the effectiveness of this programme and therefore challenge the hip therapy interventions used in RCTs [15–17] as to whether they are current best practice. However, successful application of such an approach as detailed here (personalised assessment and intervention) demands an investment of skill development, which in turn is not without cost and time restraints. Further research is required to explore the rationale on cohorts of people with FAIS.

5. Conclusions

This proof-of-concept case report supports the hypothesis that testing for MCIs can inform a targeted cognitive movement control retraining program, and improve symptoms, activity limitations, participation restrictions and quality of life in an elite rower with persistent hip pain and FAIS. To date, trials on the efficacy of movement retraining on FAIS have not been directed by individual movement assessment. This study illustrates the value of bespoke assessment to direct retraining and suggests a potential benefit to the patient-focused outcomes and cost effectiveness of management of FAIS. The targeted movement retraining program changed biomechanical and neurophysiological measures, indicating less excursion of pelvic tilt and improved muscular control of the pelvis, in particular anterior tilt. Further clinical trials are warranted to assess for movement control impairments to guide interventions.

Supplementary Materials: The following are available online at http://www.mdpi.com/2411-5142/4/2/24/s1, Cognitive Movement Retraining Programme: Key Rehabilitation Strategies for Movement Control Impairments (uncontrolled movement).

Author Contributions: conceptualization, S.M., M.W., K.B.-S. and M.S.; methodology, S.M. and M.W.; software, M.W.; formal analysis, S.M. and M.W.; investigation, S.M., M.W. and K.B.-S.; resources, M.S.; data curation, S.M. and M.W.; writing—original draft preparation, S.M.; writing—review and editing, S.M., M.W., K.B.-S., N.B. and M.S.; visualization, S.M.; supervision, M.S.; project administration, M.S.; funding acquisition, M.S.

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Conflicts of Interest: Sarah Mottram is an employee of Movement Performance Solutions Ltd., who educate and train sports, health and fitness professionals to better understand, prevent and manage musculoskeletal injury and pain that can impair movement and compromise performance in their patients, players and clients. The company did not have any influence on the results of the study or the preparation of the manuscript. The remaining authors have no conflicts of interest. No financial support or equities were provided by Movement Performance Solutions.

Appendix A

Table A1. The Foundation Matrix report detailing the site direction and threshold of movement control impairments found pre-intervention.

Higher Priority	Lower Priority	Assets:
Low threshold: alignment and coordination		
Shoulder Anterior Tilt (Left) Shoulder Drop (Left) Shoulder Winging (Left–Right) Low Back/Pelvis Rotation (Left) Low Back/Pelvis Sidebend (Right) Hip Rotation Medial (Right) Hip Anterior Translation (Left) Foot Inversion (Right) Foot Pronation (Left–Right)	None	Upper Back Lower leg
High threshold: strength and speed		
Shoulder Drop (Left–Right) Shoulder Forward Glide (Left–Right) Shoulder Hitch (Right) Shoulder Tilt (Left–Right) Low Back/Pelvis Extension Low Back/Pelvis Rotation (Right) Low Back/Pelvis Sidebend (Left–Right) Foot Inversion (Left–Right) Foot Pronation (Left–Right)	None	Upper Back Hip Lower Leg

Appendix B

Table A2. The Foundation Matrix report detailing the site direction and threshold of the individual's movement control impairments post-intervention week 16.

Higher Priority	Lower Priority	Assets:
	Low threshold: alignment and coordination	
None	Shoulder Anterior Tilt (Left) Shoulder Winging (Left–Right) Foot Inversion (Right)	Upper Back Low Back/Pelvis Hip Lower Leg
	High threshold: strength and speed	
Upper Back Rotation (Right)	Shoulder Winging (Left–Right) Shoulder Anterior Tilt (Left–Right) Low Back/Pelvis Sidebend (Right) Hip Rotation-Medial (Left)	Lower Leg Foot

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ORIGINAL ARTICLE

A novel cadaveric study of the morphometry of the serratus anterior muscle: one part, two parts, three parts, four?

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Abstract The serratus anterior is portrayed as a homogeneous muscle in textbooks and during functional activities and rehabilitation exercises. It is unclear whether the serratus anterior is composed of subdivisions with distinctive morphology and functions. The purpose of this study was to determine whether the serratus anterior could be subdivided into different structural parts on the basis of its segmental architectural parameters. Eight formalin-embalmed serratus anterior muscles were dissected and the attachments of each fascicle documented. Orientation and size of each fascicle were measured and the physiological cross-sectional area (PCSA) calculated. Three subdivisions of the serratus anterior were identified. A new finding was the discovery of two distinctive fascicles attached to the superior and inferior aspects of rib 2. The rib 2 inferior fascicle had the largest PCSA (mean 1.6 cm^2) and attached, with the rib 3 fascicle, along the medial border of the scapula to form the middle division. The rib 2 superior and rib 1 fascicles attached to the superior angle of the scapula (upper division). Fascicles from ribs 4–8/9 attached to the inferior angle of the scapula (lower division). Mean fascicle angle relative to a vertical midline reference and PCSA for each division were 29° and 1.3 cm^2 (upper), 90° and 2.2 cm^2 (middle) and 59° and 3.0 cm^2 (lower). This novel study demonstrated the presence of morphologically distinct serratus anterior subdivisions. The results of this study will inform the development of optimal techniques for the assessment, treatment and rehabilitation of this architecturally complex muscle in shoulder and neck pain.

Keywords Anatomy · Cadaver · Neck pain · Serratus anterior · Shoulder pain

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Introduction

The accurate assessment of serratus anterior muscle activity is critical to establishing its role in disorders of the shoulder and neck. However, it may be inappropriate to extrapolate the activation of one part of the serratus anterior to the muscle as a whole if it consists of morphologically and functionally distinct subdivisions. Previous electromyographic (EMG) studies have mostly examined the activity of the serratus anterior as a relatively homogeneous muscle during a variety of functional activities and rehabilitation exercises (Alizadehkhaiyat et al. 2015; Huang et al. 2015; Maenhout et al. 2016; San Juan et al. 2016). Typically these studies use electrodes only in one location on the muscle to evaluate the effect of functional activities and exercises on the serratus anterior as one whole muscle. There are no current guidelines or literature to recommend EMG sensor locations to distinguish muscle activity in individual subdivisions of the serratus anterior (SENIAM, Surface Electromyography for the Non-Invasive Assessment of Muscles, http://www.seniam.org). Distinct subdivisions have been demonstrated within numerous skeletal muscles in cadaveric dissection studies (Gottschalk et al. 1989; Johnson et al. 1994). These anatomical subdivisions are used to inform electrode placement on different parts of the muscle for the accurate determination of muscle activity in each subdivision. No previous studies have used cadaveric dissection to quantify the segmental architectural parameters of the serratus anterior to establish morphologically based subdivisions to inform EMG electrode placement.

The primary role of the serratus anterior is to stabilize the scapula against the thorax and control scapular motion during movements of the shoulder (Lear and Gross 1998; Smith et al. 2003; Castelein et al. 2015). Clinically, dysfunction of the serratus anterior has been implicated in musculoskeletal disorders including shoulder and neck pain (Cools et al. 2014; Castelein et al. 2015). Thus in clinical practice the focus is to use exercise-based therapeutic interventions targeting the serratus anterior in the rehabilitation of patients with shoulder or neck pain (Ebaugh et al. 2005; Witt et al. 2011; Holmgren et al. 2012; Worsley et al. 2013; Cools et al. 2014). However, there is no current literature to recommend effective exercises that target individual subdivisions of the serratus anterior. The delineation of serratus anterior subdivisions will enable the development of guidelines for the accurate placement of surface EMG electrodes and the creation of efficacious serratus anterior strength training and neuromuscular coordination exercises in patients with neck and shoulder pain (Ludewig and Cook 2000; Helgadottir et al. 2011; Sheard et al. 2012; Worsley et al. 2013).

The serratus anterior is typically portrayed as a homogeneous muscle that consists of 9–10 fascicles uniformly arising from ribs 1–8/9 and attaching along the medial border of the scapula (Drake et al. 2010; Moore et al., 2010). In the five primary research studies to examine the morphology of the serratus anterior using cadaveric dissection (Table 1), the muscle is inconsistently subdivided into one, two or three parts. Each subdivision is postulated to have distinctive actions at the scapula (Cuadros et al. 1995; Smith et al. 2003; Ekstrom et al. 2004; Bertelli and Ghizoni 2005; Nasu et al. 2012). No studies have quantified the segmental architectural parameters of the serratus anterior, including fascicle orientation, length and thickness, tendon length and physiological cross-sectional area (PCSA), to establish morphologically based functional subdivisions. Therefore the purpose of this cadaveric study was to determine whether the serratus anterior could be subdivided into different structural parts on the basis of its segmental architectural parameters. The results of this study will be used to inform the placement of SEMG electrodes for the accurate measurement of serratus muscle activity and the development of effective exercises for the management of shoulder and neck pain.

Materials and methods

Eight serratus anterior muscles from formalin-embalmed Caucasian cadavers (one female; three males) aged 69–96 years (mean 84; SD 12 years) were dissected at the Centre for Learning Anatomical Sciences, University of Southampton, UK. Anatomical examination was performed in accordance with the Human Tissue Act, UK (2004), and Anatomy Act, UK (1984), and the study was approved by the institutional ethics committee.

The skin and fascia of the torso and the pectoralis major and minor muscles were removed. The clavicle was disarticulated at the sternoclavicular and acromioclavicular joints and the brachial plexus, axillary vessels and their branches removed to expose the serratus anterior in its entirety (Fig. 1). The fascicular anatomy of the serratus anterior was described and quantified. A fascicle was defined as a bundle of muscle fibers with distinct and identifiable attachments to a rib. The muscle fiber angle of each fascicle was measured at the superior and inferior borders of each rib attachment using a flexible clear plastic goniometer (baseline 360°, measured to the nearest 1.0°). Muscle fiber angle was measured with respect to a vertical midline reference that passed through the suprasternal notch superiorly and the pubic symphysis inferiorly (Fig. 1). Starting from the caudal end of the serratus anterior, each fascicle was systematically detached from its respective rib and followed to its attachment on the scapula from which it was also removed. The sites of attachment were demarcated using colored ink (Cancer Diagnostics Inc., USA), photographed, measured and recorded. The length of the inferior aspect of each rib attachment site and its distance from the vertical midline reference were measured (to the nearest 0.1 cm) using a flexible tape to accommodate the curvature of the thorax (Fig. 2).

After each fascicle had been removed, measurements were made of its size (Fig. 3). If present, tendon lengths at the rib and scapular attachments were measured. After removing the tendinous fibers at each end of the fascicle, the length of its muscle fibers was measured. The thickness of each fascicle was measured at its midpoint and within 10 mm of each attachment end. All length and thickness measures were made from the inferior border of the fascicle using calibrated digital calipers (Absolute Digimatic Calipers CD-6″CX, Mitutoyo Corporation, Japan, measured to 0.01 mm). The volume of the fascicle was measured by submerging it in water, with no splash or loss of water and allowing time for any bubbles to rise to the surface, in a calibrated 100-ml measuring cylinder (VOLAC, Poulten and Graf, Barking, UK) and recording the fluid displacement to the nearest ml after the fascicle had sunk. The PCSA of each fascicle was calculated by

Table 1 Summary of previously reported studies of serratus anterior (SA) morphology

Study	Nasu et al. (2012)	Cuadros et al. (1995)	Smith et al. (2003)	Ekstrom et al. (2004)	Bertelli and Ghizoni (2005)
No. SA (cadavers)	10 (5)	40 (27)	13 (8)	Unspecified (2)	15 (Unspecified)
Gender	4 M; 1F (Japanese)	Unspecified	3F; 5 M	Unspecified	Unspecified
Fixation	Embalmed	Fresh	Unspecified	Unspecified	Fresh
Method(s)	Dissection of whole SA to show structure and innervation of each part	Dissection of lower SA to determine vascular supply	Dissection of upper SA to document attachments	Dissection of whole SA to determine optimal locations for sEMG electrodes	Dissection of whole SA to show structure and innervation of each part
Divisions	Superior part: superior angle and medial border of scapula Middle part: ribs 2–3 to medial border of scapula Inferior part: inferior angle of scapula	Lower part: ribs 6–10 to inferior angle of scapula	Upper: ribs 1–2 (46 %), rib 2 (31 %), rib 1 (15 %) or rib 2–3 (8 %) to superior angle of scapula	Upper part: ribs 1–4 to medial border of scapula Lower part: below rib 4 to inferior angle of scapula	Upper portion: ribs 1–2 to the superior medial border of the scapula Intermediate portion: ribs 2–4 to medial border of scapula Lower portion: ribs 3–8 to inferior angle of scapula
Measures	None	Lower SA flap: Dimensions mean 18.0 ± 1.9 × 9.0 ± 0.8 (min 12.0 × 8.0; max 21.0 × 15.0) cm Area mean 164 ± 40 (min 96; max 300) cm^2	Upper SA: Length mean 6.9 ± 1.2 (min 4.8; max 9.0) cm Girth mean 6.1 ± 1.5 cm (min 3.0; max 8.5) cm	None	None
Proposed functions	Superior part: anchor Inferior part: upper rotation of the scapula	Unspecified	Upper SA: compressive load to scapulothoracic joint to anchor/stabilize scapula, anterior tilt of scapula	Upper part: abduction or protraction of the scapula Lower part: upward rotation of the scapula	Upper portion: scapular protraction Lower portion: scapular stabilization

dividing the fascicle volume by its length (Johnson et al. 1994; Bogduk et al. 1998; Phillips et al. 2008).

The serratus anterior was photographed using a digital camera (Nikon Coolpix 5400, Nikon Corporation, Tokyo, Japan) fixed to a tripod (GX-86, OSAWA, Japan), and images were uploaded onto a computer. Descriptive data were presented using mean and standard deviation values for each serratus anterior fascicle.

Fourteen randomly selected fascicles were used for the determination of intra-observer reliability (measurements made 1 week apart by the same observer) and inter-observer reliability (measurements made on the same day by a second observer trained and blinded to the results of the first observer) for each of the measures. Reliability was examined using intra-class correlation coefficients (ICCs). All analyses were performed using SPSS version 17.0 for Windows (SPSS Inc., Chicago, IL, USA) and Microsoft Office Excel 2003 (Microsoft Corp., Redmond, WA, USA).

Results

Based on the fascicle attachment sites and fiber angles, the serratus anterior was found to consist of three divisions: upper (rib 1 and 2^S fascicles attached to the medial and superior borders of the scapula that form the superior angle); middle (rib 2^I and 3 fascicles that passed to the medial border); lower (rib 4–8/9 fascicles attached at the inferior angle).

At first sight, the in situ serratus anterior muscle appeared to consist of nine fascicles attaching continuously along the medial border of the scapula. Further dissection revealed up to ten distinct fascicles attached between ribs 1

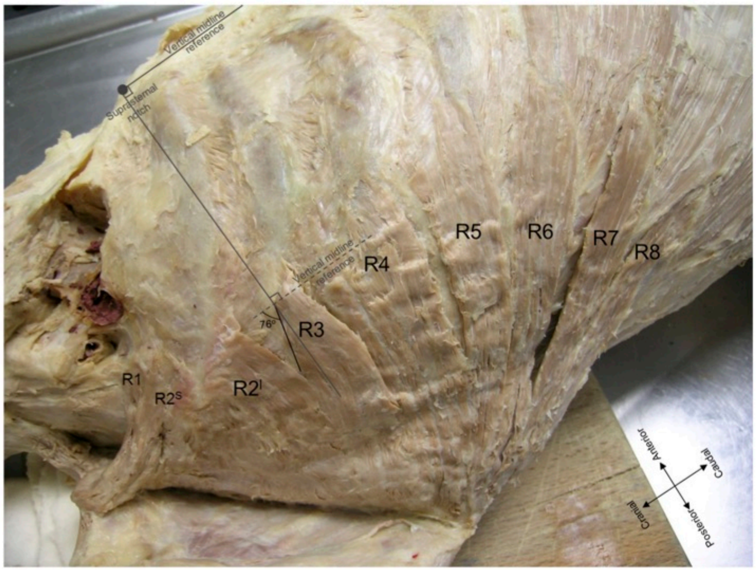

Fig. 1 Lateral view of the *right side* of the thorax, clavicle removed and scapula displaced from the thoracic cage, showing the rib 1 (*R1*) to rib 8 (*R8*) fascicles of the intact serratus anterior muscle. Two fascicles attach to the superior ($R2^S$) and inferior ($R2^I$) aspect of the second rib. The R1 fascicle is partially obscured by the $R2^S$ fascicle on this view. The measurement of the muscle fiber angle, measured in situ using a flexible goniometer with respect to a *vertical midline* reference that passed through the suprasternal notch superiorly and the pubic symphysis inferiorly, is depicted for the measurement of the fiber angle at the superior aspect of the right rib 3 fascicle

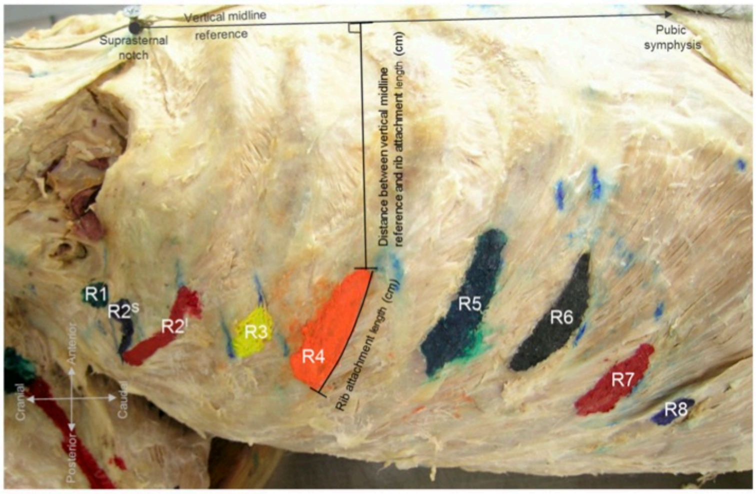

Fig. 2 Lateral view of the *right side* of the thorax, clavicle removed and scapula displaced from the thoracic cage, showing the rib 1 (*R1*) to rib 8 (*R8*) fascicle rib attachments demarcated by *colored ink* following removal of the serratus anterior muscle. The rib 2 inferior ($R2^I$) and superior ($R2^S$) fascicles attached along the inferior border of rib 2 and the superior aspect of rib 2 and first intercostal muscle, respectively. The measurement in situ of the length of each rib attachment and its distance from the *vertical midline* reference using a flexible tape measure is depicted for the *right* rib 4 fascicle

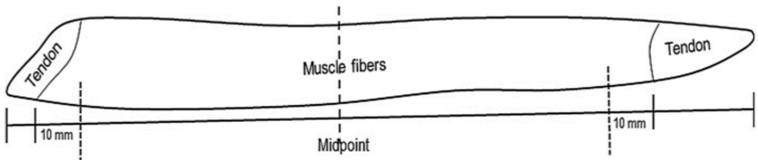

Fig. 3 The length (*solid lines*) of the muscle fibers and tendons at either end (if present) were measured for each fascicle. The thickness (*dashed lines*) of each fascicle was measured at its midpoint and at 10 mm from each end. All measures were made using calibrated digital calipers along the inferior edge of the fascicle

and 9 that arose from the superior angle, inferior angle or medial border of the scapula (Figs. 1, 2, 5). Two distinct fascicles were found to attach to rib 2 and are referred to as the rib 2^S (rib 2 superior) and rib 2^I (rib 2 inferior) fascicles, based on their rib 2 attachment sites (Figs. 2, 4). In four muscles (three right, one left), the fascicles extended between ribs 1 and 8 with no rib 9 fascicle present. Three small accessory muscle fascicles, with variant muscle fiber angle and/or rib attachment site, were observed (left and right rib 6 and right rib 5). The rib 1 fascicle was absent in one right serratus anterior.

The fibers of the lower division attached to ribs 4–8/9 and passed posteriorly and, to varying degrees, superiorly around the thoracic cage to converge via a common tendon that attached to the inferior angle of the scapula (Fig. 5). Attachment was predominantly to the anterior surface of the inferior angle with the lower three fascicles attaching to the inferior aspect of the inferior angle and extending to the

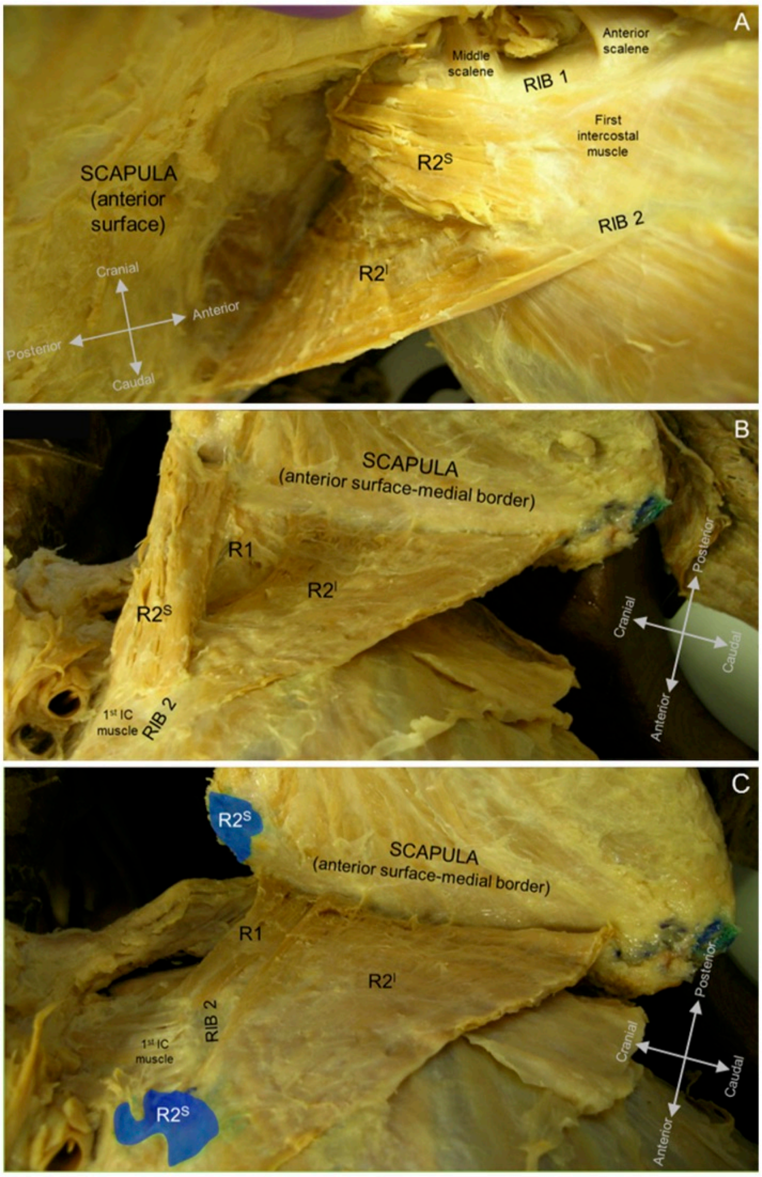

Fig. 4 Anterolateral view of the thorax, clavicle removed and scapula displaced from the thoracic cage. The rib 3–9 serratus anterior fascicles have been removed to show the attachments of the rib 2 inferior (*R2*^{I}) fascicle, between the medial border of the scapula and the inferior border of rib 2, and the rib 2 superior (*R2*^{S}) fascicle, between the superior angle (superior border) of the scapula and the superior aspect of rib 2 and the first intercostal muscle (1st IC), and the rib 1 (*R1*) fascicle, between the superior angle (medial border) of the scapula and rib 1. **a** *Right side* with the R1 fascicle not visible. **b** *Left side* with the scapula lifted to display the R1 fascicle. **c** *Left side* with the R2^S fascicle removed (attachment sites demarcated) to show the R1 fascicle and the entirety of the R2^I fascicle

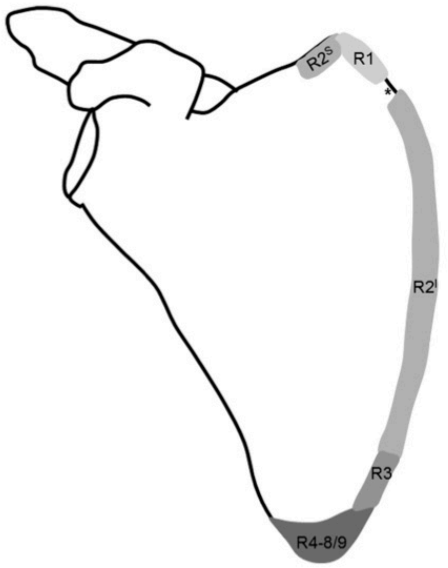

Fig. 5 Schematic illustration of serratus anterior fascicle attachments to the right anterior scapula. The rib 2 inferior (*R2^I*) fascicle attached along the majority of the medial border of the scapula with the rib 3 (*R3*) fascicle. The rib 1 and rib 2 superior (*R2^S*) fascicles attached to the medial and superior borders of the superior angle, respectively. In half of the muscles dissected, a gap was present between the attachments of the R1 and R2^I fascicles. The rib 4–8/9 fascicles attached to the inferior angle of the scapula

posterior surface. In two muscles, the rib 4 fascicle extended a short distance along the medial border where it was continuous with the rib 3 fascicle. Muscle fibers of the lower four fascicles interdigitated with the external oblique muscle fibers and/or attached to the overlying fascia at their rib attachment. In two muscles, the rib 9 fascicles attached directly to fascia covering the external oblique, rather than the rib.

The middle division predominantly consisted of the rib 2^I fascicle, which attached along the curved inferior border of rib 2, ending posteriorly at the anterior aspect of the posterior scalene muscle attachment. Its fibers passed posteriorly to attach along the length of the medial border of the scapula, where it was continuous with the rib 3 fascicle inferiorly and rib 1 fascicle superiorly, with a small gap separating the attachments in approximately half of muscles (Fig. 5).

The rib 2^S and rib 1 fascicles of the upper division attached to the superior aspect of rib 2 and rib 1, inferior to the middle scalene muscle attachment, respectively (Fig. 4). In 75 % of muscles, the attachment extended to the fascia of the first intercostal muscle. The fibers of both the rib 1 and rib 2^S fascicles passed posteriorly and superiorly to attach to the anterior surface of the superior angle of the scapula (Figs. 4, 5). The rib 1 fascicle attached to the medial border and the rib 2^S fascicle to the superior border of the superior angle in all but one of the muscles. The rib 2^S fascicle obscured the attachments of the rib 1 and 2^I fascicles and was removed first in order to access and measure the angles of the rib 1 fascicle and the superior border of the 2^I fascicle (Fig. 4).

The dimensions of each fascicle are presented in Tables 2, 3 and 4. The mean (SD) distance between the vertical midline reference and rib attachment for each division was 11.4 (1.4) cm (upper), 12.4 (1.1) cm (middle) and 14.6 (3.4) cm (lower). The fascicles of the lower division had the longest (medial to lateral) rib attachment 'footprint' and the upper division fascicles the shortest (Table 2). The rib 2^I fascicle was the largest [mean (SD) PCSA 1.6 (0.2) cm^2] (Table 3). If present, the rib 9 fascicle had the smallest mean (SD) PCSA of 0.3 (0.2) cm^2. The mean (SD) PCSA of the remaining fascicles ranged from 0.5 (0.1) cm^2 to 0.8 (0.3) cm^2 (Table 3). The mean (SD) PCSA for each division of the muscle was 1.3 cm^2 (upper), 2.1 cm^2 (middle) and 3.0 cm^2 (lower). The length of the tendon at each end of the fascicle ranged from no tendinous fibers present to 9.1 mm at the rib attachment and 13.5 mm at the scapular attachment (Table 4). Thickness of the fascicle was greatest at the scapular end compared to the midpoint and rib end (Table 4).

The ICC values for intra-observer ($ICC_{3,1}$) and inter-observer ($ICC_{2,1}$) reliability were good to excellent for all measurements (Table 5) (Cicchetti 1994). The majority of measurements were excellent (0.85–0.99). The measurements of the fascicle angle and thickness and the size of the rib attachments were the least reliable within raters (0.64–0.68).

Discussion

Distinct subdivisions have been identified within numerous skeletal muscles. This study is the first to confirm the presence of similar subdivisions within the serratus anterior muscle based on characteristic architectural parameters: upper (rib 1 and 2^S fascicles attached to the medial and superior borders of the scapula that form the superior angle), middle (rib 2^I and 3 fascicles that passed to the medial border) and lower (rib 4–8/9 fascicles attached at the inferior angle). A novel finding was that the rib 2 fascicle consisted of two parts with the rib 2^I fascicle attaching to the majority of the medial border of the scapula. The presence of these subdivisions requires consideration in the clinical assessment of the serratus anterior muscle using EMG, ultrasound and MRI as well as the development of rehabilitation exercises. The identification of serratus anterior subdivisions with distinctive

Table 2 Muscle fiber angle measured relative to a vertical midline reference (between the suprasternal notch and pubic symphysis) at the superior and inferior aspect of the rib attachment, distance to the medial end of the rib attachment from the vertical midline reference and medial-lateral dimension of the fascicle attachment at the rib for each fascicle of the serratus anterior muscle

Fascicle	No. fascicles	Fiber angle (°) at the rib attachment		Rib attachment dimensions (cm)	
		Superior aspect	Inferior aspect	Midline to rib attachment	Rib attachment
Rib 1	7	27.3 (17.1)	27.7 (16.2)	10.3 (0.7)	2.2 (0.7)
Rib 2^S	8	25.8 (18.7)	29.9 (16.8)	12.3 (1.3)	3.0 (0.6)
Rib 2^I	8	40.9 (17.8)	92.9 (8.4)	12.1 (1.0)	4.6 (1.2)
Rib 3	8	76.1 (9.0)	86.3 (7.1)	12.7 (1.3)	3.3 (1.0)
Rib 4	8	70.6 (12.4)	78.4 (9.4)	12.0 (1.0)	4.6 (1.3)
Rib 5	8	75.4 (8.6)	71.0 (9.6)	11.4 (1.0)	5.3 (1.7)
Rib 6	8	64.0 (7.6)	62.8 (10.2)	12.9 (0.9)	4.8 (1.1)
Rib 7	8	47.8 (8.8)	56.1 (6.5)	15.6 (1.5)	4.5 (1.3)
Rib 8	8	41.6 (10.5)	40.0 (14.3)	18.4 (2.1)	3.6 (1.5)
Rib 9	4	35.0 (7.7)	27.8 (15.5)	21.7 (0.3)	2.2 (1.5)

Mean (standard deviation)

Rib 2^S rib 2 superior fascicle, *rib 2^I* rib 2 inferior fascicle

Table 3 Length, volume and physiological cross-sectional area (PCSA) (volume divided by length) for each serratus anterior fascicle, identified by their respective rib attachment

Fascicle	No. fascicles	Length (cm)	Volume (ml)	PCSA (cm^2)
Rib 1	7	8.5 (1.5)	4.3 (1.4)	0.5 (0.1)
Rib 2^S	8	8.2 (0.9)	6.4 (2.1)	0.8 (0.3)
Rib 2^I	8	9.5 (2.2)	15.4 (1.4)[a]	1.6 (0.2)[a]
Rib 3	8	12.6 (1.4)	6.1 (2.5)	0.5 (0.2)
Rib 4	8	14.4 (2.2)	8.5 (2.5)	0.6 (0.1)
Rib 5	8	16.3 (1.8)	8.9 (2.4)	0.6 (0.2)
Rib 6	8	15.9 (2.4)	7.8 (1.4)	0.5 (0.1)
Rib 7	8	16.7 (1.6)	9.1 (3.6)	0.5 (0.2)
Rib 8	8	16.1 (3.1)	8.5 (2.4)	0.5 (0.2)
Rib 9	4	13.2 (2.4)	4.3 (2.6)	0.3 (0.2)

Mean (standard deviation)

Rib 2^S rib 2 superior fascicle, *rib 2^I* rib 2 inferior fascicle

[a] For the calculation of rib 2^I PCSA, the mean length of the fascicle along its superior and inferior borders was used [superior border length 7.7 (1.1) and inferior border length 11.3 (1.3) cm]

attachment sites and fascicle angle suggests that these subdivisions do not move and stabilize the scapula in the exact same manner.

The present results support the upper division having a role in controlling and anchoring the superior angle during scapular rotation because of the short thick rib 1 and 2^S fascicles attached to both borders of the superior angle of the scapula and orientated closer to the vertical compared to middle and lower division fascicles. Previous authors have proposed that the serratus anterior anchors the scapula by pulling the superior angle to the ribs to enable rotation of the scapula by influencing the main axis of scapular rotation (Gregg et al. 1979; Hamada et al. 2008, Martin and Fish 2008; Nasu et al. 2012). Interestingly, we observed these fibers passing anteriorly from the scapula to the ribs suggesting these fibers do have a role in anchoring the superior angle to the ribs and controlling movements of the scapula by influencing the axis of rotation, which changes during elevation. We propose that the upper division, because of its attachment to both the superior and medial borders that form the superior angle and the inferior orientation of the fibers as they pass to the ribs, could play a role in controlling external rotation of the scapula by anchoring the superior angle. Relative upward rotation of the scapula is maintained by keeping the acromion above the superior angle. The authors also suggest that the upper division, by anchoring the superior angle to ribs 1 and 2 (positioned inferior to the superior angle), helps to maintain optimum scapular orientation and relative scapula upward rotation, by keeping the superior angle inferior to the acromion. The longer tendon of the rib 2^S fascicle at the scapular end could contribute to directing the forces required to anchor the superior angle.

The rib 2^I fibers passed virtually horizontally to their rib attachment, and despite being the thinnest fascicle (Table 4), we discovered the fascicle had the largest PCSA. We suggest this supports the role of the middle division for producing external rotation (and controlling internal rotation) of the scapula at the acromioclavicular joint and then protraction of the clavicle at the sternoclavicular joint, as described by Ludewig and Reynolds (2009). However, before protraction can occur, the line of action of the

Table 4 Thickness of the muscle fibers within each fascicle, measured along the inferior border at the mid-point of each fascicle and 10 mm from both the lateral scapular end and the medial rib end following removal of the tendon

Fascicle	Fascicle thickness (mm)				Tendon length (mm)			
	No. fascicles	Scapula end	Midpoint	Rib end	No. fascicles	Scapula end	No. fascicles	Rib end
Rib 1	7	3.1 (1.3)	2.5 (2.1)	2.0 (0.8)	1	1.8	1	3.5
Rib 2^S	8	3.1 (1.2)	3.4 (1.7)	2.6 (1.0)	2	12.0 (14.5)	4	3.2 (1.7)
Rib 2^I	8	2.4 (0.6)	1.9 (1.3)	1.3 (0.5)	4	4.8 (0.6)	4	3.9 (0.8)
Rib 3	8	3.4 (1.2)	1.9 (0.8)	1.5 (0.8)	7	6.0 (4.1)	1	9.1
Rib 4	8	4.2 (1.6)	2.0 (0.6)	0.9 (0.3)	7	7.0 (4.4)	3	2.4 (1.1)
Rib 5	8	4.2 (1.4)	3.8 (1.5)	1.1 (0.4)	6	5.0 (2.2)	3	6.4 (3.9)
Rib 6	8	4.0 (2.4)	3.8 (0.8)	1.4 (0.3)	6	5.5 (3.0)	4	3.3 (1.1)
Rib 7	8	4.9 (2.1)	4.0 (1.3)	1.5 (0.3)	7	4.9 (2.1)	1	2.4
Rib 8	8	3.5 (1.1)	4.0 (1.0)	1.8 (0.7)	8	5.5 (2.4)	1	8.4
Rib 9	4	2.7 (1.5)	2.5 (0.9)	1.3 (0.4)	2	13.5 (2.5)	1	6.1

The length of the tendon, when present, was measured along the inferior border at the lateral scapular end and the medial rib end of each fascicle. Mean (standard deviation)

Rib 2^S rib 2 superior fascicle, *rib* 2^I rib 2 inferior fascicle

Table 5 Reliability for each measure of serratus anterior fascicle morphometry

Fascicle measurement	Intra-observer ($ICC_{3,1}$)	Inter-observer ($ICC_{2,1}$)
Angle	0.64	0.94
Length	0.96	0.94
Thickness	0.85	0.74
Volume	0.96	0.85
Rib attachment to midline	0.99	0.97
Rib attachment	0.68	0.70

Ratings for clinical significance of ICC values (Cicchetti 1994): <0.40 poor; 0.40–0.59 fair; 0.60–0.74 good; 0.75–1.00 excellent

ICC intraclass correlation coefficient

serratus anterior will first pull the medial border and inferior angle of the scapula towards the chest wall, creating external rotation of the scapula. This external rotation of the scapula will stabilize the scapula as protraction of the clavicle at the sternoclavicular joint occurs. The rib 2^I fascicle attachment along the medial border of the scapula suggests this fascicle has a role in controlling scapular winging, which is a commonly observed problem in shoulder pain and dysfunction (Ludewig and Reynolds 2009). Because of the large PCSA of this fascicle, consideration needs to be given to its force capabilities and the influence this could have on controlling scapular winging. Calculation of the force capacity of the serratus anterior fascicles and subdivisions would help support this proposition.

The lower division fascicles were of approximately equal dimensions and PCSA. At the scapula, the muscle attachment is concentrated at the inferior angle and projects anteriorly and inferiorly to attach to ribs 8/9–4 at an angle increasing from 28° to 78°. The fibers will pull the inferior angle laterally around the chest wall (away from the midline), and because the axis of rotation is slightly inferior to the spine of the scapula, this supports a primary role of upward rotation of the scapula. The increasing angle of the fibers to rib 4 suggests the fiber orientation changes in relation to the rib position to optimize the pull of the inferior angle laterally. The role of upward rotation is confirmed by EMG studies of the lower division where exercises that create upward rotation of the scapula produce greater EMG activity compared to straight scapular protraction exercises (Moseley et al. 1992; Ekstrom et al. 2004). In participants with shoulder impingement, Worsley et al. (2013) reported delayed onset and early termination of serratus anterior activity using surface EMG, and less posterior tilt and upward rotation with three-dimensional kinematic analysis. EMG was recorded from the lower serratus anterior division as described by Ludewig and Cook (2000). The results of the present study are in agreement with previous authors that have suggested the lower division produces upward rotation (Ludewig et al. 2004; Roren et al. 2013) and controls downward rotation (Worsley et al. 2013). Activity of the serratus anterior has been noted in scapular posterior tilt exercises (Ha et al. 2012), and posterior tilt has been noted in people with long thoracic nerve lesions (Roren et al. 2013) supporting its role in scapular posterior tilt. The authors suggest posterior tilt is produced by the inferior laterally directed fibers of the lower division and the middle division is likely to contribute to controlling anterior tilt too by keeping the medial border close to the thoracic spine. Further research is needed to explore the degree of muscle activity for each serratus anterior subdivision during a variety of rehabilitation exercises. Greater delineation of which exercises optimally recruit each subdivision is of interest to clinicians as this may inform the development of more effective treatment and exercise programs.

The optimal EMG electrode placement location for the serratus anterior is not known. Clearly the serratus anterior has distinctive divisions that require consideration when evaluating this muscle and developing effective clinical tests and training strategies. The results of the present study provide the anatomical basis for the development of new protocols for surface EMG electrode placement to ensure that electrodes are positioned parallel to muscle fibers and on muscle rather than tendon (Hermens et al. 2000). Furthermore, the detailed morphometry reported in the present study can be used to establish standardized sites and valid and reliable methods of applying ultrasound and MR imaging for the measurement of muscle geometric parameters and functions for each serratus anterior subdivision (Talbott and Witt 2013). To measure muscle activity in the upper division, it is suggested that electrodes be placed on the more superficial rib 2^S fascicle rather than the rib 1 fascicle, given that they have equivalent fiber angle and PCSA. The inferior part of the rib 2^I fascicle, where the muscle fibers are oriented at 90° to the midline, is recommended for electrode placement on the middle division. Not only is the rib 2^I fascicle the broadest and most distinctive in the middle division, it also represents the majority of the middle division PCSA. The rib 6 fascicle is recommended for electrode placement on the lower division as it is both accessible and characteristic of this division. The placement of surface electrodes on both the rib 2^S and 2^I fascicles is likely to be challenging because of the overlying scapula and presence of nearby muscles such as the pectoralis major and minor. Future research using ultrasound and diffusion tension magnetic resonance imaging in living subjects is recommended to refine these cadaveric-based recommendations and enhance the accurate acquisition of serratus anterior muscle activity from each subdivision.

The present study has a number of limitations. First, the cohort studied was small, but as an exploratory study the results are promising, and, in our view, because of the clinical relevance of the serratus anterior in shoulder and neck pain, a larger study is warranted. A larger sample size would enable investigation of the consistency of the serratus anterior morphology and prevalence of the variations documented in this and previous studies (Eisler 1912; Cuadros et al. 1995; Smith et al. 2003). Second, the quantification of muscle volume, using the Archimedes' principle of fluid displacement, can be affected by the extent of muscle hydration (Ward and Lieber 2005) and the presence of air bubbles. Attempts were made to minimize these factors by the use of 5 % formaldehyde solution for embalming and allowing time for any bubbles to rise to the surface. In addition, while great care was taken to define the muscle attachment and remove it directly from its attachment site, it is possible that some periosteum may have been removed in this process, creating an artifact. Finally, the challenge of measuring the serratus anterior fiber angle is exemplified by the lower intra-observer reliability value compared to other measurements (Table 5). Different measurement methods have been employed to measure the muscle fiber angle but no gold standard exists (De Foa et al. 1989; Johnson et al. 1994; Ackland et al. 2008). Serial dissection combined with digitization and three-dimensional modeling in cadavers and diffusion tensor imaging in vivo are promising new methods for the visualization and quantification of muscle architecture throughout the entire muscle volume (Lee et al. 2015). A future study powered for the determination of anatomical variants and with some methodological improvements, such as digital measurement of architectural parameters, is justified.

The findings from this novel study of the fascicular architectural morphometry of the serratus anterior muscle suggest that the muscle consists of three distinctive subdivisions (upper, middle and lower). Although these preliminary results need confirmation with a larger study, they will inform accurate location of electrodes during SEMG assessment of the serratus anterior and the functional relevance of the subdivisions. The findings have clinical implications for the development of optimal techniques for the assessment, management and rehabilitation of this architecturally complex muscle.

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Compliance with ethical standards

Conflict of interest Sarah Mottram is Director of Movement Performance Solutions, Ltd., and educates and trains sports, health and fitness professionals to better understand, prevent and manage musculoskeletal injury and pain that can impair movement and compromise performance in their patients, players and clients. The remaining authors have no conflict of interest to declare. No financial support or equities were provided by Movement Performance Solutions or other sources.

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Research article

Intra and Inter-Rater Reliability of Screening for Movement Impairments: Movement Control Tests from The Foundation Matrix

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Abstract
Pre-season screening is well established within the sporting arena, and aims to enhance performance and reduce injury risk. With the increasing need to identify potential injury with greater accuracy, a new risk assessment process has been produced; The Performance Matrix (battery of movement control tests). As with any new method of objective testing, it is fundamental to establish whether the same results can be reproduced between examiners and by the same examiner on consecutive occasions. This study aimed to determine the intra-rater test re-test and inter-rater reliability of tests from a component of The Performance Matrix, The Foundation Matrix. Twenty participants were screened by two experienced musculoskeletal therapists using nine tests to assess the ability to control movement during specific tasks. Movement evaluation criteria for each test were rated as pass or fail. The therapists observed participants real-time and tests were recorded on video to enable repeated ratings four months later to examine intra-rater reliability (videos rated two weeks apart). Overall test percentage agreement was 87% for inter-rater reliability; 98% Rater 1, 94% Rater 2 for test re-test reliability; and 75% for real-time versus video. Intraclass-correlation coefficients (ICCs) were excellent between raters (0.81) and within raters (Rater 1, 0.96; Rater 2, 0.88) but poor for real-time versus video (0.23). Reliability for individual components of each test was more variable: inter-rater, 68-100%; intra-rater, 88-100% Rater 1, 75-100% Rater 2; and real-time versus video 31-100%. Cohen's Kappa values for inter-rater reliability were 0.0-1.0; intra-rater 0.6-1.0 for Rater 1; -0.1-1.0 for Rater 2; and -0.1-1 for real-time versus video. It is concluded that both inter and intra-rater reliability of tests in The Foundation Matrix are acceptable when rated by experienced therapists. Recommendations are made for modifying some of the criteria to improve reliability where excellence was not reached.

Key words: Movement control, movement impairments, screening, reliability.

Introduction

Emphasis on injury prevention is increasing in sport to reduce the health and economic impact of injury and maximise performance (Bahr and Krosshaug, 2005; McBain et al., 2012 Peate et al., 2007; Turbeville et al., 2003; Tyler et al., 2006; Webborn, 2012; Zazulak et al., 2007). Injury results when body tissue is unable to cope with the applied stresses, whether acute or chronic (McBain et al., 2012). Multiple factors increase the risk of injury and invariably injuries result from a combination of factors including; history of pain, previous injury, acquired hypermobility, aerobic fitness, changes in the control of movement (Bahr and Krosshaug, 2005; McBain et al., 2012; Plisky et al., 2006, Roussel et al 2009; Webborn, 2012; Yeung et al., 2009). Various strategies have been employed to reduce both extrinsic causes of injury (e.g. unavoidable direct contact trauma and intrinsic causes of injury (e.g. non-contact injury related to overuse, or poor movement technique, efficiency or control), but consistent predictors of injury are still lacking (Butler at al., 2010; Garrick, 2004).

Although pre-season screening has been part of the routine in sport for some time, some approaches lack the complexity required to identify movement impairments relevant to everyday activities. In other testing protocols, there has been an emphasis on measuring joint mobility, muscle extensibility, endurance and strength, as well as fitness tests and physiological testing (Butler et al., 2010; Mottram and Comerford, 2008; Myer et al., 2008; Yeung et al., 2009). Such tests have a role in providing benchmarks for rescreening reference during the season and post injury, and provide some indication of limitations that need addressing but many do not predict injury (Butler et al., 2010).

Currently, the strongest predictor of injury is previous injury (Chalmers, 2002; Fulton et al., 2014; Tyler et al., 2006) but this is clearly not desirable as an ongoing predictor. It has been suggested that a change may occur following injury, which could be explained as a change in motor control (Kiesel et al., 2009; MacDonald et al., 2009). Central nervous system mediated motor control is vital to both production and control of movement (Hodges and Smeets 2015), and more recently the focus of assessing movement impairments and developing movement retraining programs has moved towards optimising the control of movement (Cook et al., 2006a; Cook et al., 2006b, Luomajoki et al., 2010, Worsley et al., 2013).

Quality of movement, specifically control of movement, is now being recognised as an important element of assessment of movement efficiency as well as range (Simmonds and Keer, 2007; Roussel et al., 2009). The identification and correction of movement control impairments have been recognised as an important part of assessing and rehabilitating injury (Comerford and Mot-

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tram, 2001; Comerford and Mottram 2012; Luomajoki et al., 2007; Sahrmann, 2014) but attention is now focussing on protocols to evaluate uninjured groups to determine non-symptomatic deficits within the kinetic chain of functional movement patterns that might predispose to injury (Cook et al., 2006a; 2006b; Kiesel et al., 2007; Peate et al., 2007; Plisky et al., 2006; Roussel et al., 2009). This new perspective in screening has been used to develop a tool known as The Performance Matrix (TPM). This tool employs generic multiple joint tasks that are functionally relevant, but not necessarily habitual, and have been modified to test the cognitive control of movement. The protocol identifies inefficient control of movement (weak links) within the kinetic chain indicating the presence of uncontrolled movement (UCM; Comerford and Mottram, 2012). The key features of TPM that differ from other movement screens include: 1) detailing the site and direction of UCM to direct specific targeted retraining; 2) evaluation of low and high threshold UCM explained below; 3) testing for active control of movement to benchmark standards (not natural or habitual movement patterns), 4) evaluation of movement control and not pain, which, when present, does not mean a fail in this screen, as some people have good control in the presence of pain; 5) the software produces a risk algorithm that helps establish retraining priorities (although this has yet to be validated). 6) A unique classification of subgroups of movement control impairments as high risk, low risk and assets.

Uncontrolled movement is described for the purpose of this screening process as a lack of ability to cognitively co-ordinate and control motion efficiently to benchmark standards at a particular body segment (Comerford and Mottram, 2012). A loss of the ability to control movement is thought to increase the loads and stresses on the joint, increasing susceptibility to injury (Sterling et al., 2001).

Motor control is key to optimising control of movement and ensuring the coordinated interplay of the various components of the movement system: the articular, myofascial and connective tissue, and neural systems. Changes in motor control result in altered patterns of recruitment, with inhibition in some muscle groups and increased activity in others (Hodges and Richardson, 1996; O'Sullivan, 2005; Sterling et al., 2001). Altered muscle recruitment strategies and motor control impairments may result from previous injury (O'Sullivan, 2005; Sterling et al., 2001) fatigue, stiffness i.e. loss of range of joint of motion or myofascial extensibility (Cook et al., 2006a), or muscle imbalances (Cook et al., 2006a; Sahrmann, 2002). Impaired motor control can also lead to compensatory movements (Roussel et al., 2009; Zazulak et al., 2007).

The Foundation Matrix forms part of The Performance Matrix movement screening system (Movement Performance Solutions Ltd). The Performance Matrix is the generic name for the entire group of screening tests developed by Movement Performance Solutions. The Foundation Matrix, is the most commonly used screening tool in the database, and is the entry level screen, which is designed to identify performance related inefficient control of movement in the kinetic chain. This entry level matrix was therefore chosen for the present study. Other screens in the database are sport specific, e.g. football and golf, or region specific e.g. low back, or occupation specific e.g. office worker or tactical athlete, such as fire fighter or police. Using a series of multi-joint functionally relevant tests (listed in Table 2), The Foundation Matrix screen evaluates movement control efficiency. The protocol assesses both the site and direction of uncontrolled movement in different joint systems, and evaluates these control impairments under two different, but functionally relevant physiological situations, low (Figure 1 for example of test 1) and high threshold testing (Figure 2 for example of test 9). The screening tool assesses deficits in the control of non-fatiguing alignment and co-ordination skills in what is referred to as 'low threshold' tasks, and assesses deficits in movement control during fatiguing strength and speed challenges in what is referred to as 'high threshold' tasks (Mottram and Comerford 2008). The objective of The Foundation Matrix screening tool is to provide the assessor with details of the site, direction, and threshold of uncontrolled movement, to allow for the development of a specific training programme. When considering the utility of a test, both reliability (intra and inter-rater) and validity must be established.

Although some movement control tests have been evaluated for reliability and validity (Luomajoki et al., 2007; Roussel et al., 2009; Teyhen et al., 2012), the reliability of the battery of movement control tests in The Foundation Matrix has not been examined. Therefore, the aim of the present study was to establish both the intra and inter-rater reliability of experienced therapists in rating performance of nine of the 10 tests from The Foundation Matrix. These include five low threshold tests of alignment and coordination control and four high threshold tests of strength and speed control. The reason for excluding one of the high threshold tests is explained below.

Methods

Participants

Twenty university sports students (11 females; 9 males; aged = 21 ± 3) participated in the study. Participants were asymptomatic and were excluded if they had a present pathology, injury, pain, surgery, a musculoskeletal injury within the past six months, or were pregnant. Prior to screening, all participants gave written, informed consent, and the Research Ethics Committee of the University approved the study.

Raters

Two experienced musculoskeletal therapists, who were specialists in the field of movement control, assessed the efficiency of movement control during the performance of tests. Therapist 1 had 23 years' experience in musculoskeletal physiotherapy and 14 years' experience in movement control assessment and re-training, and Therapist 2 had 16 years' experience in musculoskeletal physiotherapy and 7 years' experience in movement control assessment and re-training.

Protocol

Both therapists assessed participants using the battery screening protocol comprising nine movement control tests (Table 2). Each participant was scheduled to a 45 minute session. Both therapists completed the screening process at the same time independently, without conferring, during which time testing was video recorded for retrospective analysis of intra-rater reliability of assessing test performance on another occasion (Butler et al., 2012; Fersum et al., 2009; Luomajoki et al., 2007). Six digital cameras (Casio exfh20) were used to record participants performing the tests, and were set up to give anterior, posterior and lateral views. Tripods and angle adjustment allowed for variation in positioning of the tests. All participants wore black lycra shorts and females wore a sports top that allowed observation of movement and bony landmarks.

Table 1. Order of performance of tests.

The tests are reported by the name of the test in The Foundation Matrix (TFM). NB Test 6 was not included in the present study (see Methods section of text)
Standing Tests
1- Double Knee Swing (Low threshold TFM Test 1)
2- Single leg ¼ squat+hip turn (Low threshold TFM Test 2)
3- Controlled shoulder internal rotation (Low threshold TFM Test 4)
4- Split squat+fast feet change (High threshold TFM Test 9)
5- Lateral stair hop + rotational landing control (High threshold TFM Test 10)
Floor Tests
6- Bridge + straight leg lift & lower (Low threshold TFM Test 3)
7- 4 point - arm reach forward and back (Low threshold TFM Test 5)
8- Plank + lateral twist (High threshold TFM Test 7)
Wall test
• One arm wall push (Low threshold TFM Test 8)

Movement control tests

Nine of the 10 movement control tests of The Foundation Matrix were used (Table 1). Each of the 10 tests in the Foundation Matrix has five criteria posed as questions (n = 50) which require an observational judgement regarding the person's ability to adequately control movement to a pass or fail benchmark standard. Not all movement evaluation criteria on movement control faults could be evaluated. Some movement evaluation criteria involving the ability to control movement could not be included due to: 1) appropriate views not being possible to obtain clearly on video; 2) passive tests of movement restrictions not being part of the present study of observational testing; 3) tests requiring the use of a pressure biofeedback unit which gave objective measures of control; and 4) criteria assessing repositioning ability (proprioception). Therefore, 40 of the 50 movement evaluation criteria, and 9 of the 10 tests were used in the study. Test 1, the Double Knee Swing (Figure 1) has been described and illustrated previously (McNeill 2014). Each test was rated by a series of movement evaluation criteria (Table 2) posed as questions, aimed at identifying observational markers that indicate uncontrolled movement. Each criterion is given a pass or fail response. The final report identifies both performance assets and weak links (movement control impairments), which are the priority risk factors (Comerford, 2006; Mottram and Comerford, 2008).

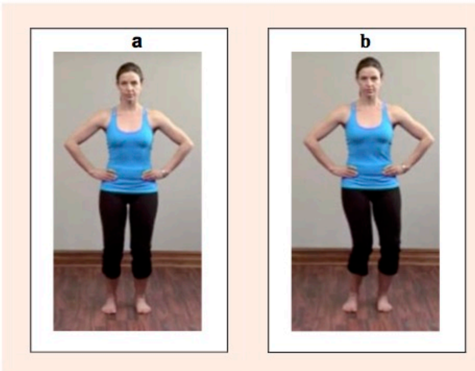

Figure 1. Test 1, a) start position, b) end position double knee swing.

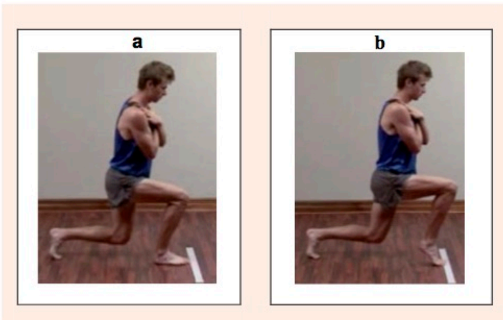

Figure 2. Test 9, a) start position, b) end position split squat and fast feet change

Prior to testing, the study co-ordinator and therapists reviewed the assessment criteria to ensure consistency. The participant was taught each test following standardised instruction (summarised in Table 2) regarding how to perform the movement task correctly using visual, audio and kinaesthetic techniques. Before the screening process commenced, each participant viewed a video of the correct performance of the movements and Therapist 1 verbally explained each test in detail, and the main objectives. Because these tests evaluate the performance of an unfamiliar skill of movement control, and not a natural functional movement, a period of familiarisation is necessary so as not to skew the results for the wrong reason. It is important that a person is judged to fail a test because of poor active cognitive control of movement, not because they were unsure of what the control task required.

Experience has shown that four to six practice attempts with feedback and cueing was sufficient for people with good control abilities to learn and pass the test (Luomajoki et al., 2007; Worsley et al., 2013).

Table 2. Test details and scoring system for movement efficiency criteria.

Test Details	Marking Criteria
Double Knee Swing	
In standing, bend the knees into a ¼ squat position Swing both legs simultaneously to the left, then right to 20° of hip rotation The pelvis should not rotate or laterally shift to follow the knees Keep the 1st metatarsal head fully weight bearing on the floor.	Can you prevent the pelvis and back rotating to follow the legs? Can you prevent side bending of the trunk and lateral movement of the shoulders? Can you keep the trunk upright and prevent further forward bending at the hips? Can you prevent the foot from turning out as the knee swings out to 20°? Can you prevent the big toe from lifting as the knee swings out to 20°?
Single Leg ¼ Squat + Hip Turn	
Stand on one foot keeping pelvis and shoulders level, and arms across the chest Take a small knee bend 30°, and hold this position for 5 seconds Then moving the trunk and pelvis together, turn 30° away from the standing foot Hold this position for 3 seconds Turning back to the front straighten the knee Repeat the movement, standing on the other leg	Can you keep the pelvis facing straight ahead as you lower into the small knee bend and hold the position for 5 seconds? Can you prevent side bending of the low back and trunk in the small knee bend position or during the rotation? Can you prevent the trunk from leaning further forward in the small knee bend position? Can you prevent the (WB) knee turning in across the foot to follow the pelvis as you turn the pelvis away from the standing foot? Can you prevent the (WB) arch from rolling down or toes clawing?
Bridge + Heel Lift + Single Straight Leg Raise & Lower	
Lying in crook lying position, lumbopelvic neutral position, arms folded across the chest Maintaining position, lift the pelvis just clear of the floor (about 2 cm) Lift heels into full plantar flexion Maintaining position, slowly take weight off one foot and straighten that knee keeping thighs level. Then slowly raise the straight leg, moving the thigh up towards the vertical position, then slowly lower the straight leg (extend the hip) to horizontal Return to crook lying and repeat on the opposite side	Can you prevent low back flexion as the straight leg raises? Can you prevent low back extension as the leg lowers? Can you prevent pelvic rotation against asymmetrical single leg load?
Controlled Shoulder Internal Rot	
Stand tall with the scapular in neutral position, shoulder abducted to 90°, 15-30° forward of the body in scapular plane, elbow flexed to 90° Ensure humeral head and shoulder blade, are in neutral position Maintaining upper arm and scapular position, rotate the arm to lower the hand down towards the floor. Monitor the scapular at the coracoid with one finger and the front of humeral head W with another finger during medial rotation There should be 60° of independent medial rotation of the shoulder joint	Can you prevent the upper back and chest from dropping forward as you rotate the arm? Can you prevent the upper back and chest from turning as you rotate the arm? Can you prevent the coracoid rolling or tilting forward? Can you prevent forward protrusion of the humeral head?
4 Point - Arm Reach Forward And Back	
Start on all fours, knees under the hips and hands under the shoulders Position the spine, scapulae and head in neutral mid position Maintaining neutral position, shift body weight onto one hand, slowly lift the other arm off the floor to reach behind you to 15° shoulder extension. Then move to lift and reach the arm in front to ear level. Repeat to other side	Can you prevent either shoulder blade hitching? Can you prevent either shoulder blade dropping or tilting forward? Can you prevent winging of the weight-bearing shoulder blade? Can you prevent forward protrusion of the head of the shoulder joint as the non weight-bearing arm extends?
Plank + Lateral Twist	
Lie face down supported on elbows, positioned under shoulders and forearms across the body, side by side. Maintaining the knees and feet together, bend the knees to 90°, and push the body away from the floor taking the weight through the arms into a ¾ plank, keeping a straight line with legs, trunk and head. Maintaining lumbopelvic neutral position shift the upper body weight onto one elbow, during the weight shift the body should move laterally (approx 5-10cm). Turn the whole body 90° from the (WB) shoulder to a ¾ side plank, the trunk, pelvis and legs should turn together and remain in a straight line. Return to starting position again maintaining position. Repeat the movement to the other side	Can you prevent the weight-bearing shoulder blade dropping? Can you prevent the weight-bearing shoulder blade winging or retracting? Can you prevent forward protrusion of the humeral head of the weight-bearing shoulder joint as you turn onto one arm? Can you prevent the low back from arching? Can you prevent the pelvis from leading the twist as you turn from the front plank position towards the side plank position?

Table 2. Continued.

Test Details	Marking Criteria
One Arm Wall Push	
Stand tall in front of a wall, hold the arm at 90° flexion, hand placed on the wall, scapular in neutral, move the feet one foot length further back away from the wall, lean forward and take body weight on the hand Keeping the shoulder blade, trunk and pelvis in neutral, slowly bend the elbow to lower the forearm down to the wall Lower the elbow so the forearm is vertical and fully weight-bearing against the wall, then push the body slowly away from the wall to fully straighten the elbow Do not allow the trunk and pelvis to rotate or arch towards the wall. Repeat with the other arm	Can you prevent the upper back from flexing or rounding out as the arm pushes away from the wall? Can you prevent the upper back from rotating? Can you prevent the weight-bearing shoulder blade from hitching or retracting? Can you prevent forward tilt or winging of the weight-bearing shoulder blade?
Split Squat + Fast Feet Change	
Step out with one foot (4 foot length), feet facing forwards and arms folded across chest Keeping the trunk upright, drop down into a lunge, rapidly switch feet in a split squat movement, control the landing Then lift the heel of the front foot to full plantarflexion and hold this heel lift in the deep lunge for 5 seconds, then lower the heel and without straightening up, rapidly switch feet in a split squat movement, control the landing After the landing, again lift the heel of the front foot to full plantarflexion and hold this heel lift in the deep lunge for 5 seconds Repeat the heel lift twice with each leg in the forward position	Can you prevent side bending of the trunk? Can you keep the trunk upright and prevent the trunk leaning forward at the hips towards the front foot? Can you prevent the front knee moving in across the line of the foot? Can you prevent the foot from turning out or the heel pulling in as you land? Can you prevent the heel of the front foot from rolling out during the heel lift?
Lateral Stair Hop + Rotational Landing Control	
Stand side on to a box/step (approx 15 cm) with the feet together, and arms by your side Keeping the back straight bend the knees into a 'small knee bend' position, lift the outside leg off the floor to balance on the inside leg Hop laterally up onto the box/step / keeping the back upright and controlling the landing into the 'small knee bend' position Hold this position for 5 seconds Then hop back down off the box to rotate through 90° to land on the same leg turning to face away from the box/step Repeat with the other leg	Can you prevent the trunk or pelvis from rotating? Can you prevent side-bending of the trunk as you land on the hop down? Can you prevent the body from leaning forwards at the hip as you land? Can you prevent the landing knee turning in across the foot as you hop down? Can you prevent the arch from rolling down or toes clawing as you hop down?

Once the participant indicated that they clearly understood how to perform the test, the test procedure was commenced and scored independently by the assessors. Each test was repeated up to three times, and the two therapists recorded their scores of performance. The order of the tests was standardised (Table 1) to ensure all participants were assessed the same way as recommended by Luomajoki et al., (2007). The test sessions took approximately 40 minutes.

Scoring system

As the participant carried out the movement task, Therapists 1 and 2 recorded their observation on the efficacy the participant's ability to control movement by a number of criteria, which involved scoring a pass or fail to a set of criteria (Table 2). Since the intention of The Foundation Matrix is to measure impairment, a low score indicates less impairment and a high score indicates greater impairment. Therefore, fail is rated as 1 and pass is rated as 0. After the therapist had recorded their observations, the participant was taught the next test and the procedure repeated until all nine tests had been recorded.

Inter-rater reliability was determined from the scoring conducted real-time, reflecting routine practice. Conversely, intra-rater reliability was established from the video recordings of the screening protocol as this ensured consistency of performance of the movement control tests. Videos were downloaded onto a hard drive, where each participant was identified by number only. Videos were then edited using Final cut pro (2001).

The video recordings were distributed to Therapists 1 & 2 for intra-rater reliability evaluation four months following the real-time assessment of the movement control tests. This time lapse was due to logistical reasons, including the need to edit and compile the videos ready for assessment, which was conducted two weeks apart, as previously described by Luomajoki et al., (2007). The video recordings were viewed on a laptop with a maximum of three views per test based on Ekegren et al., (2009). As before, the Therapists' observations on the control of movement were recorded. All scoring sheets were transcribed to an Excel spread sheet for analysis.

Statistical analysis

Percentage agreement is presented for each site and direction of uncontrolled movement (identified as a fail) as a whole score (e.g. left and right sides combined). The overall score for an individual is the sum of the scores across all individual site and direction failures of each test. The reliability of this overall score was assessed using intraclass correlation coefficient (ICC) and classified according to Fleiss (2007). Real-time versus video- and intra-rater reliability were assessed with the ICC(1,1) model (with subjects as the only effect), and inter-rater reliability was assessed with the ICC(2,1) model (with subjects and judges both considered random effects).

Agreement was examined using the Kappa test. Cohen's Kappa (κ) is commonly used to assess agreement between different judges when ratings are on a nominal scale (Cohen, 1960). Kappa describes agreement beyond chance relative to perfect agreement beyond chance (as opposed to percentage agreement, which describes agreement relative to perfect agreement). Kappa was used to assess inter- and intra-rater agreement, across each individual criterion of each test; Kappa was also used to evaluate agreement between real-time and video assessment by one rater. All Kappa values are presented with 95% confidence intervals. Where movement evaluation criteria of a test are applicable to two sides of the body (e.g. left leg and right leg), Kappa is presented for each separate side in order to preserve the assumption of independence between observations.

Results

The analysis was based on nine tests, comprising varying numbers of components, i.e. criteria about movement control (between 3 and 5 components in each test, totalling 40 criteria). These criteria may be further broken down into left- and right-hand side for assessment using κ, referred to here as sub-components (35 of the criteria may be broken down into two sub-components, making 75 criteria in total).

Table 4. Reliability of overall scores: intraclass correlation coefficients (ICC).

	Scenario	ICC (95% CI)	
ICC(1,1)	Intra-rater (1)	.96	(.93, .99)
	Intra-rater (2)	.88	(.78, .98)
	Real-time versus video	.23	(.00, .65)
	Intra-rater (1)	.96	(.93, .99)
ICC(2,1)	Inter-rater agreement	.81	(.50, .93)

Composite analysis

Overall percentage test agreement (as a combination of each test's criteria) were: 86.5% for inter-rater reliability; 97.5% for test re-test reliability in Rater 1 and 93.9% in Rater 2; and 74.5% for real-time versus video. Table 3 shows the percentage agreement for each of the nine tests for the four scenarios examined.

The ICCs for overall agreement (combination of all tests) for each scenario were excellent between raters (0.81) and within raters (Rater 1, 0.96; Rater 2, 0.88) but poor for real-time versus video (0.23) (Table 4).

Criteria analysis within movement tests

More detailed analysis of the movement evaluation criteria in each test revealed variability within each of the reliability scenarios, indicating which criteria were more reliable than others.

Inter-rater agreement

The percentage agreement for criteria ranged from 67.5 to 100% (mean overall agreement 86.5%), with only two of the 40 criteria in Table 5 with less than 70% agreement. Each test as a whole had agreement above 70% as shown in Table 3. Agreement varied between tests, with some having ratings for all criteria agreeing >80% (Test 3, 4, 7) and for one test >90% (Test 8). Tests 5 and 9 were less reliable, with criteria below 75% (Test 5 D 67.5%; Test 9 D 72.5 and E 67.5%). The percentage agreements for the inter-rater reliability are presented in Figure 3, which highlights the level of agreement for each test.

Cohen's Kappa with 95% confidence intervals, and criteria percentage agreement results are presented in Table 5 for inter-rater reliability of real-time observations. Kappa values ranged from 0-1, with κ>0.6 for 36 of the 75 criteria, and 12 of these with κ>0.8. A further six criteria had κ=N/A and hence 100% agreement. Kappa values were generally similar between the right and left sides, although there were some exceptions. The range of values for criteria within each test varied, although some tests could be identified as having particularly good reliability or otherwise. For example, Tests 4 and 8 had generally high Kappa and percentage agreement values, whereas Test 9 had some low Kappa scores that were reflected by lower percentage agreement than other tests.

Intra-rater agreement

Intra-rater agreement for repeated ratings from videos is presented for Rater 1 in Table 6 and Rater 2 in Table 7. Reliability for Rater 1 was good, with percentage agreement values ranged from 87.5 to 100% (mean 97.5%). Kappa values ranging from 0.64 to 1.0, with only 5/75 criteria (right and left shown) with κ<0.70 (10/75 were κ=N/A) and all nine tests containing values of 1.0.

Table 3. Overall test agreement (as a combination of each test's criteria) and overall scenario agreement (as a combination of all tests).

Test	Test agreement (%)			
	Inter-rater	Intra-rater (1)	Intra-rater (2)	Real-time / video
1	85.0	99.5	93.0	76.9
2	83.5	99.5	90.5	77.5
3	87.2	95.0	100.0	67.9
4	95.0	97.1	93.6	74.6
5	81.9	96.7	94.1	67.8
7	91.7	98.3	90.0	82.2
8	95.0	94.3	96.4	87.1
9	77.5	97.5	95.5	77.3
10	87.0	97.0	96.0	58.3
Overall	86.5	97.5	93.9	74.5

Table 5. Inter-rater agreement for real-time assessment: Cohen's kappa with 95% confidence intervals and percentage agreement for criteria (n = 20 except * n = 18)

Test	Criteria	Left-hand side Kappa (95% CI)		Right-hand side Kappa (95% CI)		Criteria agreement (%)
1	A	.86	(.59-1.00)	.88	(.64-1.00)	95.0
	B	.55	(.19-.90)	.38	(-.02-.78)	75.0
	C	.74	(.40-1.00)	.74	(.40-1.00)	90.0
	D	.58	(.19-.98)	.70	(.39-1.00)	85.0
	E	.66	(.31-1.00)	.43	(.01-.85)	80.0
2	A	.22	(-.33-.76)	.00	N/A	82.5
	B	.57	(.14-1.00)	.32	(-.27-.90)	85.0
	C	.12	(-.28-0.52)	.27	(-.17-.71)	75.0
	D	.88	(.64-1.00)	.76	(.45-1.00)	92.5
	E	.76	(.45-1.00)	.38	(-.07-.82)	82.5
3	A		.77 (.35-1.00)			95.0
	B		.80 (.54-1.00)			90.0
	C	.00	N/A	.34 *	(-.17-0.85)	84.2
4	A		1.00 (1.00-1.00)			100.0
	B	N/A	N/A	N/A	N/A	100.0
	C	1.00	(1.00-1.00)	.64	(.01-1.00)	97.5
	D	.69	(.38-1.00)	.68	(.35-1.00)	85.0
5	A	N/A	N/A	.00	N/A	97.5
	B	.63	(.24-1.00)	.74	(.40-1.00)	87.5
	C	.38	(-.07-.82)	.39	(-.03-.81)	75.0
	D	.24	(-.17-.65)	.13	(-.33-.58)	67.5
7	A	.00	N/A	.00	N/A	95.0
	B	.77	(.35-1.00)	.44	(-.20-1.00)	92.5
	C	.77	(.35-1.00)	.86	(.59-1.00)	95.0
	D		.66 (.308-1.00)			85.0
	E	.89	(.67-1.00)	.58	(.22-.95)	87.5
8	A		N/A N/A			100.0
	B	.80	(.54-1.00)	.89	(.67-1.00)	92.5
	C	N/A	N/A	N/A	N/A	100.0
	D	.69	(.29-1.00)	.78	(.50-1.00)	90.0
9	A	.29	(-.14-.73)	.63	(.24-1.00)	77.5
	B	.68	(.35-1.00)	.60	(.26-.94)	82.5
	C	.55	(.19-.90)	.89	(.67-1.00)	87.5
	D	.38	(-.12-.87)	.15	(-.28-.57)	72.5
	E	.35	(-.07-.76)	.30	(-.06-.66)	67.5
10	A	.44	(-.20-1.00)	.000	N/A	92.5
	B	.39	(-.09-.86)	.615	(.15-1.00)	85.0
	C	.50	(.12-.88)	.600	(.25-.95)	77.5
	D	.64	(.01-1.00)	1.000	(1.00-1.00)	97.5
	E	.60	(.24-.95)	.634	.28-.99)	82.5

NB. Test 6 from the Performance Matrix was not included in the study, for reasons explained in the methodology section of the text

For Rater 2, Kappa values ranged from -0.1-1.0, with 35/75 criteria with κ>0.70 and seven of the nine tests containing values of 1.0. Overall percentage values ranged from 0.75 to 100% (mean 93.9%). Figure 3 illustrates these percentage intra-rater results clearly, with Rater 1 values close to or on the outer edge of the radar graph and those of Rater 2 slightly more towards the centre, while those for inter-rater and then video versus real-time becoming more central, indicating less reliability.

Real-time versus video agreement

Results for agreement between real-time and video ratings are presented in Table 8. Percentage agreement ranged from 30.8 to 100% (74.5%). Figure 3 highlights the low agreement of specific test criteria, for example 10D, which showed percentage agreement of 30.8% with correspondingly low Kappa coefficients on both the right (0.04) and left (0.04) sides (Table 8). Kappa values ranged from -0.1 to 1, with only 12 of the 75 criteria with κ>0.60 and only four κ>0.70.

Discussion

The results of the present study indicate that reliability of The Foundation Matrix movement assessment system was generally acceptable. The present findings show variable reliability, with intra-rater reliability for Rater 1 being highest, then intra-rater reliability for Rater 2, then inter-rater reliability, with comparison between video and real-time assessments showing less robust reliability for some criteria.

The three statistical analyses (Kappa, ICC, percentage agreement) and ways of managing data (group and individual criteria) produced different levels of agreement but had been used in similar studies of movement tests (see section on comparison with other movement screening reliability studies), enabling comparison

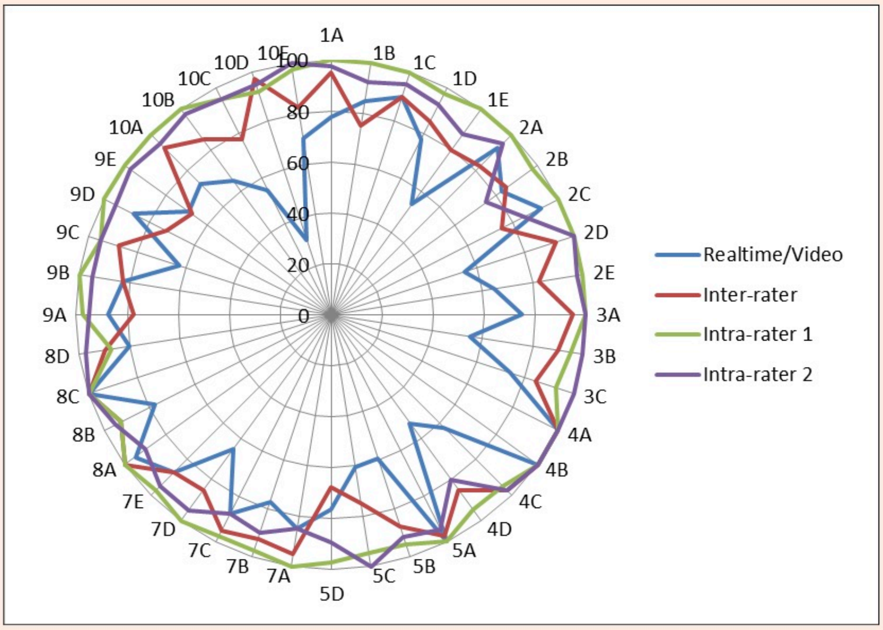

Figure 3. Radar graph of percentage agreement, indicating intra and inter-rater reliability and agreement between real-time and video ratings.

with earlier studies. The ICC values for each test overall, gave the strongest reliability results, followed by percentage agreement and then Kappa, the suitability of which is questioned for the type of data being examined. As discussed below, overall analyses of tests do not allow weaknesses in specific test criteria to be revealed, as illustrated by the present study, which provides the opportunity to modify the assessment tool to make it more robust.

Inter-rater reliability

Agreement between the two raters real-time was generally good, although the strength of agreement depended on which analysis method was used, i.e. overall analysis was excellent with ICC = 0.81 (Table 4) and 86.5% for percentage agreement, whereas analysis of individual criteria produced lower percentage scores (although only 2/40 criteria had <70% agreement) and Kappa values that indicated the majority had moderate to poor agreement, with approximately 50% of the values $\kappa<0.60$ (Table 5).

The more detailed analyses enable the criteria to be scrutinized to determine aspects contributing to relative weakness in the overall scores in Table 3. For example, Test 9, the split squat with fast feet change (Figure 2) showed the lowest percentage agreement (78%). When assessing an individual performing a high speed manoeuvre, such as the split squat with fast feet change, it becomes more challenging to observe deviations from the standardised criteria. A reliability study of another screening tool also found that more complex movements are more difficult to judge consistently (Reid et al., 2014). Indeed, the more experienced rater (Therapist 1) showed slightly better intra-rater reliability on this test than Therapist 2 (98% and 96% agreement respectively; Tables 6 & 7). Some of the criteria for this test focused on the control of the alignment of the lower limb; "Can the foot be prevented from turning out or the heel from pulling in as they land?" and "Can the heel of the front foot be prevented from rolling out (inversion) during the heel lift?" Such observations may be difficult to detect, especially as some movement would occur while the limb is stabilising.

The study used three processes to help increase consistency in evaluating these more difficult movement control tasks. Firstly, the testers had undergone the same training in the delivery and scoring of the movement control tests. Secondly, each movement control task was taught to the participant the same way and the same familiarisation process was followed. Thirdly, each movement control task is a specific movement pattern to be performed the same way by all participants. The participants were instructed to perform the task to a standard benchmark level. The test is not an evaluation of their natural or habitual movement pattern or strategy. Although the marking criteria regarding such observations are very precise, it may be necessary to modify the instructions to the therapist and state a time point by which stabilisation should have occurred.

Intra-rater test re-test reliability

Intra-rater agreement was excellent for overall analyses for both raters (ICC 0.96 Rater 1; 0.88 Rater 2; percentage agreement 97.5% Rater 1; 93.9% Rater 2). As for inter-rater reliability, strength of agreement was lower for the analysis of individual criteria, although this was still good (Tables 6 and 7).

Table 6. Rater 1 intra-rater agreement: Cohen's kappa with 95% confidence intervals and criteria percentage agreement (n = 20 except *n = 19, ** n= 18).

Test	Criteria	Left-hand side Kappa (95% CI)		Right-hand side Kappa (95% CI)		Criteria agreement (%)
1	A	1.00	(1.00-1.00)	1.00	(1.00-1.00)	100.0
	B	1.00	(1.00-1.00)	1.00	(1.00-1.00)	100.0
	C	1.00	(1.00-1.00)	1.00	(1.00-1.00)	100.0
	D	1.00	(1.00-1.00)	.83	(.50-1.00)	97.5
	E	1.00	(1.00-1.00)	1.00 *	(1.00-1.00)	100.0
2	A	N/A	N/A	N/A	N/A	100.0
	B	1.00	(1.00-1.00)	.83	(.50-1.00)	97.5
	C	N/A	N/A	N/A	N/A	100.0
	D	1.00	(1.00-1.00)	1.00	(1.00-1.00)	100.0
	E	1.00	(1.00-1.00)	1.00	(1.00-1.00)	100.0
3	A	1.00 (1.00-1.00)				100.0
	B	.88 (.64-1.00)				95.0
	C	.64	(.01-1.00)	.64	(.01-1.00)	.64
4	A	1.00 (1.00-1.00)				100.0
	B	N/A	N/A	N/A	N/A	N/A
	C	.90	(.70-1.00)	.90	(.70-1.00)	.90
	D	.83 *	(.50-1.00)	.83 *	(.50-1.00)	.83 *
5	A	N/A	N/A	N/A	N/A	100.0
	B	.89 *	(.69-1.00)	.88 **	(.65-1.00)	94.6
	C	.83 *	(.50-1.00)	.87 *	(.63-1.00)	94.7
	D	1.00*	(1.00-1.00)	.00 *	N/A	97.4
7	A	1.00	(1.00-1.00)	1.00	(1.00-1.00)	100.0
	B	1.00	(1.00-1.00)	0.83	(.50-1.00)	97.5
	C	1.00	(1.00-1.00)	0.64	(.01-1.00)	97.5
	D	1.00 (1.00-1.00)				100.0
	E	1.00	(1.00-1.00)	0.90	(.71-1.00)	97.5
8	A	1.00 (1.00-1.00)				100.0
	B	.79	(.52-1.00)	.79	(.52-1.00)	.79
	C	N/A	N/A	N/A	N/A	N/A
	D	.61	(.11-1.00)	.61	(.11-1.00)	.61
9	A	1.00	(1.00-1.00)	.89	(.69-1.00)	97.5
	B	1.00	(1.000-1.00)	1.00	(1.00-1.00)	100.0
	C	.90	(.70-1.00)	.89	(.69-1.00)	95.0
	D	1.000	(1.00-1.00)	1.00 *	(1.00-1.00)	100
	E	1.000	(1.00-1.00)	1.00 *	(1.00-1.00)	100
10	A	1.00	(1.00-1.000)	1.00	(1.00-1.00)	100.0
	B	1.00	(1.00-1.000)	1.00	(1.00-1.00)	100.0
	C	.89	(.69-1.000)	.90	(.70-1.00)	95.0
	D	.88	(.64-1.000)	.76 *	(.45-1.00)	92.3
	E	1.00	(1.00-1.000)	.90	(.70-1.00)	97.5

When examining reliability of each of the criteria, intra-rater reliability was more robust than that between the two raters, as evidenced in (Figure 3). It is clear that some assessment criteria could be revised, to ensure greater consistency in terms of agreement. Perhaps some criteria need greater clarification regarding what constitutes a pass or fail are determined, i.e. there may need to be additional benchmarks for some of the scoring guidelines. For example, in Test 4 that assesses the control of shoulder movement in the 4 point arm reach, palpation would aid evaluation of winging of the scapula and control of the humeral head. Observation of these may also be difficult if there is additional recruitment of the anterior musculature (pectorals). With the high threshold tests, for example the split squat Test 9, one criterion is to determine if side bending of the trunk can be prevented. However, with such a dynamic test it may take a few seconds to stabilise, so loss of control would be determined by an inability to stabilise and then control side bending. This should also be considered when reflecting on the lateral stair hop (Test 10) and the ability to prevent the body from leaning forward on landing. However, a small degree of flexion would be expected but the key is the ability to correct this to then return to an upright position once landed. It may therefore be useful to have a brief period, perhaps 2-3 seconds, to allow for stabilisation before grading, e.g. in the plank and lateral twist (Test 7), and then this would ensure the scoring is made at that time point.

Real-time versus video agreement

Agreement between real-time and video assessment was lower than that for the other scenarios (ICC 0.23; overall percentage agreement 74.5%), with criteria showing lower Kappa scores and percentage agreement (Table 8). There were seven criteria that returned κ=N/A, which corresponded to 100% agreement for those criteria.

The purpose of the video recordings was to standardise the experimental conditions for examining intra-rater reliability on different occasions. However,

Table 7. Rater 2 intra-rater agreement: Cohen's Kappa with 95% confidence intervals and overall criteria percentage agreement (n = 20 except *n = 19, **n = 18).

Test	Criteria	Left-hand side Kappa (95% CI)		Right-hand side Kappa (95% CI)		Criteria agreement (%)
1	A	.83	(.50-1.00)	1.00	(1.00-1.00)	97.5
	B	.89	(.69-1.00)	.76	(.45-1.00)	92.5
	C	.90	(.71-1.00)	.90	(.71-1.00)	95.0
	D	.79	(.52-1.00)	.89	(.69-1.00)	92.5
	E	.90	(.70-1.00)	.60	(.26-.94)	87.5
2	A	.86	(.59-1.00)	.83	(.50-1.00)	95.0
	B	.69	(.38-1.00)	.31	(-.08-.71)	75.0
	C	.70	(.39-1.00)	.68	(.35-1.00)	85.0
	D	N/A	N/A	N/A	N/A	100.0
	E	N/A	N/A	.00	N/A	97.5
3	A		1.00 (1.00-1.00)			100.0
	B		N/A N/A			100.0
	C	N/A	N/A	N/A	N/A	N/A
4	A		1.00 (1.00-1.00)			100.0
	B	N/A	N/A	N/A	N/A	N/A
	C	1.00	(1.00-1.00)	1.00	(1.00-1.00)	1.00
	D	.60	(.28-.92)	.60	(.28-.92)	.60
5	A	.64 *	(.00-1.00)	.77 *	(.35-1.00)	94.7
	B	.83 *	(.50-1.00)	.44 **	(-.21-1.00)	91.9
	C	N/A	N/A	N/A	N/A	100.0
	D	-.08 *	(-.23-.08)	.83*	(.50-1.00)	89.5
7	A	.69	(.29-1.00)	.53	(.14-0.92)	85.0
	B	.00	N/A	.00	N/A	90.0
	C	.79	(.53-1.00)	.67	(.34-1.00)	87.5
	D		0.77 (0.35-1.00)			95.0
	E	1.00	(1.00-1.00)	.69	(.31-1.00)	95.0
8	A		-0.053 (-0.18-0.07)			90.0
	B	1.00	(1.00-1.00)	1.00	(1.00-1.00)	1.00
	C	N/A	N/A	N/A	N/A	N/A
	D	.00	N/A	.00	N/A	.00
9	A	.89	(.67-1.00)	.88	(.64-1.00)	95.0
	B	.88	(.64-1.00)	.88	(.64-1.00)	95.0
	C	.77	(.35-1.00)	.77	(.35-1.00)	95.0
	D	.83	(.50-1.00)	.83	(.50-1.00)	95.0
	E	1.00	(1.00-1.00)	.64	(.01-1.00)	97.5
10	A	.89 *	(.69-1.00)	.90	(.71-1.00)	94.9
	B	.64	(.01-1.00)	N/A	N/A	97.5
	C	.64	(.01-1.00)	.64	(.01-1.00)	95.0
	D	.64	(.01-1.00)	.00	N/A	95.0
	E	1.00	(1.00-1.00)	N/A	N/A	100.0

However, visibility of some test movements on the video recordings may not have been as clear compared to the real time scoring. The video cameras were set up to provide views from all sides but still this does not enable the freedom to observe from all angles and distances. Percentage agreement for Criterion 1e was 54% for real-time / video agreement and 80% for inter-rater and 100% for intra-rater (Therapist 1) and 88% (Therapist 2). The criterion scored was: "Can you prevent the big toe from lifting as the knee swings 20 degrees (inversion)?" Interpretation of this may have been different in real time, as therapists were able to move around the participant to gain the best view to observe inversion and this may have been limited on the videos.

Comparison with other movement screening reliability studies

Some examples of reliability studies using various movement screening tools are discussed here briefly. Reliability of the Functional Movement Screen (FMS) has been examined between and within raters in various studies, using the 21 point screen (e.g. Gribble et al., 2013; Onate et al., 2012; Parenteau-G et al., 2014; Schneiders et al., 2011; Smith et al., 2013; Teyhen et al., 2012). The literature generally reports substantial to excellent reliability for the FMS between raters, using videotaped or real time scoring methods. However, direct comparison between studies is limited due to differences in study designs, test viewing methods and statistical analyses used, and no study has compared real-time with video scores. For example, Schneiders et al., (2011) recorded excellent inter-rater reliability for the composite FMS testing (ICC 0.971), while the inter-rater reliability for the individual test components of the FMS tests demonstrated substantial to excellent agreement with Kappa ranging from 0.70-1.0. Onate et al. (2012) found excellent inter-rater reliability (ICC 0.98) for real-time scoring by one certified FMS specialist and a FMS novice. Teyhen et al., (2012) recorded an ICC of 0.76 for inter-rater reliability between four FMS trained physical therapy doctoral students. Smith et al., (2013) used two sessions where FMS was scored live and the inter-rater reliability was good for

Table 8. Real-time versus video agreement: Cohen's Kappa with 95% confidence intervals and criteria percentage agreement; (n = 20, except * n = 19, ** n = 18).

Test	Criteria	Left-hand side Kappa (95% CI)		Right-hand side Kappa (95% CI)		Criteria agreement (%)
1	A	.55	(.19-.90)	.43	(.01-.85)	77.5
	B	.67	(.34-1.00)	.69	(.38-1.00)	85.0
	C	.69	(.29-1.00)	.69	(.29-1.00)	90.0
	D	.46	(-.14-1.00)	.34	(.04-.64)	77.5
	E	.13	(-.16-.46)	.23 *	(-.11-.57)	53.8
2	A	.00	N/A	N/A	N/A	92.5
	B	.38	(-.12-.87)	.318	(-.27-.90)	82.5
	C	.00	N/A	.000	N/A	92.5
	D	.14	(-.16-.43)	.259	(-.08-.60)	55.0
	E	.00	(-.40-.40)	.529	(.14-.92)	65.0
3	A	.31 (-.14-.75)				75.0
	B	.10 (-.28-.48)				55.0
	C	-.08	(-.24-.08)	-.08	(-.24-.08)	-.08
4	A	1.00 (1.00-1.00)				100.0
	B	N/A	N/A	N/A	N/A	N/A
	C	.26	(-.12-.63)	.26	(-.12-.63)	.26
	D	.24 *	(-.02-.50)	.24 *	(-.02-.50)	.24 *
5	A	N/A*	N/A	N/A	N/A	100.0
	B	.18 *	(-.16-.53)	.11 **	(-.33-.55)	59.5
	C	-.02 *	(-.46-.42)	.03 *	(-.43-.48)	60.5
	D	-.09 *	(-.25-.08)	.22 *	(-.15-.58)	76.3
7	A	.00	N/A	.000	N/A	85.0
	B	-.11	(-.29-.06)	-.14	(-.33-.06)	77.5
	C	.64	(.01-1.00)	.27	(-.17-.71)	87.5
	D	.38 (.08-.67)				65.0
	E	.78	(.50-1.00)	.69	(.38-1.00)	87.5
8	A	0.00 N/A				95.0
	B	.58	(.22-.95)	.58	(.22-.95)	.58
	C	N/A	N/A	N/A	N/A	N/A
	D	.83	(.50-1.00)	.83	(.50-1.00)	.83
9	A	.73	(.39-1.00)	.66	(.31-1.00)	87.5
	B	.58	(.22-.95)	.70	(.38-1.00)	82.5
	C	.49	(.11-.88)	.07	(-.28-.43)	62.5
	D	.35	(-.17-.86)	.46 *	(-.14-1.00)	87.2
	E	.42	(.06-.78)	.38 *	(.01-.76)	69.2
10	A	.50	(.05-.95)	.00	N/A	72.5
	B	-.07	(-.48-.35)	.21	(-.24-.67)	65.0
	C	.03	(-.37-.43)	.20	(-.22-.62)	55.0
	D	.03	(-.04-.11)	.04 *	(-.04-.12)	30.8
	E	.38	(-.02-.78)	.38	(-.02-.78)	70.0

session one and two with ICCs of 0.89 and 0.87 respectively, whilst intra-rater reliability was good for each rater with an ICC from 0.81-0.91. Gribble et al., (2013) scored three video-taped subjects on two separate testing sessions one week apart and found excellent intra-rater reliability (ICC 0.96) for trained athletic trainers (ATC) with greater than six months FMS experience (n=7), an intra-rater reliability (ICC 0.77) for trainers with less than six months FMS experience (n=15), and poor intra-rater reliability (ICC 0.37) for ATC students (n=16). However, comparing scores across all participants, without classification of experience, an intra-rater ICC of 0.75 was produced (Gribble et al., 2013) but the number of subjects in that study was small (n=3). The overall ICC of 0.81 for inter-rater reliability in the present was lower than some FMS studies and higher than others. The present intra-rater reliability ICCs for the two raters (0.96 and 0.88) were comparable with the FMS findings for experienced raters and higher than less experienced raters.

Frohm et al., (2012) evaluated the inter- and intra-rater reliability of the Nine-Test Screening Battery to screen athletic movement patterns and found no significant difference ($p = 0.31$) between eight physiotherapists assessing 26 participants on two test occasions, with ICCs of 0.80 and 0.81, respectively. Using the same Screening Battery, Rafnsson et al., (2014) found excellent intra-rater reliability (ICC 0.95) between test-retest sessions. The retest had significantly higher total score than the first test ($p = 0.041$), indicating some learning effect by the participant.

The Single-limb Mini Squat (SLMS) is used to distinguish between those with knee-over-foot and knee-medial to-foot positioning. Ageberg et al., (2010) found no difference between examiners ($p = 0.317$) who assessed 25 participants, with a Kappa value of 0.92 (95% CI, 0.75 to 1.08) and 96% agreement between examiners.

Other considerations

Sample sizes for reliability testing vary widely between studies. A sample of 20 is recommended as the minimum for reliability testing (Atkinson and Nevill, 2001; Walter et al., 1998), so the present sample size was adequate.

It has been acknowledged previously that achieving good reliability from visual information can be difficult (Luomajoki et al., 2007), although it has also been suggested that with sufficient training on each test, such judgments can be enhanced. It is worth considering that the more experienced therapists in the present study and that by Gribble et al., (2013) demonstrated higher intra-rater reliability than the less experienced therapists, which is an observation consistent with other reliability studies (Luomajoki et al., 2007).

There are situations where it is not possible to assess agreement using Kappa (κ), and the phenomenon of high agreement but low Kappa scores was discussed by Cicchetti and Feinstein, (1990). In the present study, for example, if both therapists score each participant "0", κ is undefined; this is because there are no data relating to "1", and so agreement cannot be assessed across all outcomes (0 and 1). In such cases, κ was presented as "N/A" (although it is worth noting these cases always had 100% agreement on one level of the outcome, and no information regarding agreement on the other level of the outcome). There were also situations where κ was zero or negative, suggesting that agreement was no better or worse than agreement expected by chance alone, respectively. We believe this is not necessarily a true reflection of the agreement of the test criterion itself, but rather a reflection of the limited sample size – again, these situations arise when there is very little data relating to one of the outcomes (0 or 1). For example, Table 7 shows the results for criterion 8a in the intra-rater assessment for Rater 2. We observe $\kappa = -0.05$ (95% CI [-0.18, 0.07]) for this criterion, i.e. agreement is worse than that by chance, or at best very slightly better than chance, but also observe 90% agreement. The reason for low Kappa is obvious when we consider the cases where the rater scores 0: on both first and second viewings, the rater scores a single 0, but these do not coincide; therefore, we have total disagreement whenever the rater scores 0. Further investigation is needed to establish agreement adequately in such a situation.

Limitations of the study

Factors related to the research design may have impacted on the scoring of the tests. For example, participants were asked to repeat the test up to three times to allow for the two therapists to move around freely to score their ratings and to ensure the test had been recorded. This repetition may have allowed improvement in performance but there was no observed change after the initial practice sessions as described in the protocol above. When examining inter-rater reliability, it is important that each criterion (Table 2) is marked in the same order and therefore at the same time point, especially on those tests that have a greater number of marking criteria. For future research, it is recommended that: a) the number of repeat performances is standardised; and b) both therapists observe the same area of the body, and score at the same time point. Only two experienced observers (physiotherapists) were involved in the present study. For the findings to be generalizable, more observers with different levels of experience and from a range of professions need to be studied. The lack of agreement between the real-time and video scores indicates that video evaluation of movement tasks may have increased the ability to judge movement control impairments more consistently. This may have been because evaluation was made from four standardised views i.e. the four video cameras as opposed to the therapist moving around the participant whilst performing the test. For future studies comparing real-time with video evaluation, the criteria should be scored by observing from the same angle of view for the two types of assessment.

For the purposes of large epidemiological studies that require retrospective analysis to save time during testing, the most robust tests and criteria would need to be determined. The videos provided a valid means of presenting consistent performance of tests by the participants to assess intra-rater reliability of the observers.

Future research

Acceptable inter and intra-rater reliability has now been established for the tests selected from The Foundation Matrix and has indicated specific criteria that require modification to the scoring benchmarks and pass or fail guidelines (Figure 3) to improve the robustness of the tool. Reliability of other tests in The Performance Matrix needs to be established in experienced and novice therapists. The validity of the screening tool against objective markers also needs to be established, as well as sensitivity to change. An example of validity and responsiveness was demonstrated for a shoulder movement control test (from the database of tests available in The Performance Matrix series of movement screens) that was examined objectively using 3-dimensional motion analysis. That study found abnormal scapular movements in people with shoulder impingement, which improved (kinematics and recruitment) following a motor control retraining programme (Worsley et al., 2013). More comprehensive validity and reliability testing of The Performance Matrix screening system is warranted.

Conclusion

The Foundation Matrix has demonstrated good inter-rater reliability and excellent intra-rater reliability for two experienced therapists. Agreement for real-time versus video assessment was generally moderate to poor. The findings indicate the clinical utility of this screening tool in identifying performance assets and uncontrolled movements. Recommendations have been made for refining the criteria and number of repetitions of some tests to improve reliability.

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Key points

- The movement control tests of The Foundation Matrix had acceptable reliability between raters and within raters on different days
- Agreement between observations made on tests performed real-time and on video recordings was low, indicating poor validity of use of video recordings
- Some movement evaluation criteria related to specific tests that did not achieve excellent agreement could be modified to improve reliability

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Mottram, S. & Blandford, L. 2020. Assessment of movement coordination strategies to inform health of movement and guide retraining interventions. *Musculoskelet Sci Pract*, 45, 102100.

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Mottram, S., Warner, M., Booysen, N., Bahain-Steenman, K. & Stokes, M. 2019 Retraining in a female elite rower with persistent symptoms post-arthroscopy for femoroacetabular impingement syndrome: a proof-of-concept case report. *Journal of Functional Morphology and Kinesiology*, 4(2), 24

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Section B
DECLARATION BY CANDIDATE
I declare that my contribution to the above publication were as **Joint Author**

My specific contribution to the publication was:
Conceptualisation of research project hypothesis and establishing collaboration with University of Chichester. Design of experiment, and methodology. Contribution to resources, data collection, data analysis and interpretation. Writing -input into first draft 40%, and revision of the manuscript.

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Section B
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Section B
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Glossary of Terms

Cognitive Movement Control Tests .. Evaluate an individual's ability to cognitively coordinate movement at a specific joint or region (site) in a particular plane of movement (direction), under low and high threshold situations. Cognitive movement control tests (CMCTs) identify loss of movement choices by asking an individual to prevent observable movement to a benchmark standard. The cognitive element enquires on choice rather observation (Mottram and Blandford, 2020).

Coordination Variability .... The range of coordinative strategies exhibited whilst performing the movement outcome (Preatoni et al., 2013)

Exercise .... A subcategory of physical activity and defined as an activity that is planned, structured, repetitive, and aims to improve or maintain one or more components of physical fitness (World Health Organisation, 2020b).

Health of Movement .... A balance between how an individual uses their body to engage with life and an ability to display choices in movement coordination strategies.

Loss of Movement Choices .... An inability to display choices in movement; notated by site, direction and threshold® and describe the observable changes in movement coordination strategies. The working hypothesis is that loss of movement choices relate to reduced coordination variability so an individual is unable to vary coordination strategies to achieve a movement task (Mottram and Blandford, 2020). Loss of movement choices are revealed through cognitive movement control tests.

Motor Abundance .... The central nervous system has the ability to facilitate families of solutions (coordinated movements) equally able to solve a task, that are not the same over repeated trials (Latash, 2012)

Movement Coordination Strategies . Coordination is how things work together. Movement coordination strategies (MCS) are the clinically observable changes in segment and region joint configurations of the body (dynamic alignment) used by individuals during the performance of a tasks. MCS can be observed as intersegmental (joint), and these coordination strategies could be interpreted to inform on muscle synergy coordination (Mottram and Blandford, 2020).

Physical Activity ....Any bodily movement produced by skeletal muscles that requires energy expenditure, including activities undertaken whilst, working, playing, carrying out household chores, travelling, and engaging in recreational pursuits (World Health Organisation, 2020b).

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